Microkarst, Palaeosols, and Calcrete along Subaerial Disconformities in the Ordovician Daylesford Limestone, Bowan Park, Central Western New South Wales

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Accumulation of the Ordovician Daylesford Limestone at Bowan Park, west of Orange, NSW, has been repetitively interrupted by subaerial disconformities. There are distinct diagenetic and pedogenetic suites of products within diverse fossiliferous carbonate lithologies associated with the disconformities as expressed in grains and minerals, fabrics and structures, and lithologies. These include: lithoclasts, calcrete-coated and peripherally-altered lithoclasts, remanié fossils, diagenetic (internal) sediments, terrigenous mud and silica; fossil molds, enlarged fossil molds, cavities, mottles, fissures and irregular surfaces, patches of cryptocrystalline and microcrystalline calcite, bleached zones; and various lithologies such as vugular limestone, mottled limestone, massive light grey limestone, lithoclast grainstone, calcrete-ooid grainstone, calcrete-ooid packstone and wackestone, pellet packstone and wackestone, (terrigenous) mudstone, and palaeosols. Lithoclasts (of vugular limestone with diagenetic sediment) above disconformities, and the restriction of vugular limestone with variable diagenetic sediment-filled cavities beneath disconformities, indicate leaching and internal sedimentation was early and associated with subaerial exposure. The most important factor affecting profile variation is the type of host rock, i.e. grainstone *versus* muddy limestone. Palaeosols are mostly developed on muddy limestone, and leaching is most common within the altered muddy limestone, whereas for grainstones, palaeosols are generally absent, and cryptocrystalline (and microcrystalline) calcite (calcrete) patches are probably the most important diagenetic product. Beneath the disconformities, ten types of subaerially developed profiles are recognised: erosionally truncated vugular limestone with coralline encrustation on the disconformity, erosionally truncated vugular limestone without palaeosol cover, erosionally truncated vugular limestone with thin palaeosol cover, muddy limestone with thin palaeosol cover with calcrete ooids and remanié fossils, muddy limestone with thick palaeosol cover with calcrete ooids and remanié fossils, muddy limestone with marine-reworked lithoclastic and calcrete ooid grainstone and remanié fossils, solution-altered grainstone with overlying lithoclastic and calcrete ooid grainstone, thick calcrete developed on grainstone, wackestone/lime-mudstone (marl) with overlying sheet of (terrigenous) mudstone, and silicified limestone. Of the range of products and profiles, the vugular limestones stand as the most important indicators of subaerial exposure.

The information in this study provides insights into the types of subaerial diagenesis and pedogenesis operating during the Ordovician, and also into landscape setting, palaeo-hydrology and depth of the vadose zone, climate, and groundwater/rainwater alkalinity.

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KEYWORDS: calcrete, Daylesford Limestone, diagenesis, limestone, microkarst, Ordovician, pedogenesis, subaerial palaeosols.

INTRODUCTION

Detecting subaerial disconformities is important in stratigraphic and environmental studies of marine carbonate rocks in order to recognise discontinuities in the sequence, and to be able to identify and relate those specific diagenetic alteration effects which may be attendant to subaerial exposure. Diagenetic phenomena associated with subaerial exposure of marine and palustral carbonates have been documented from Pleistocene to Holocene sequences (Friedman

1964; Roehl 1967; Matthews 1967, 1968; Purdy 1968), soils (Gile et al. 1966; Reeves 1970; Read 1974; Brown and Woods 1974) and pre-Quaternary sequences (Dunham 1969a, 1969b; Francis 1986; Driese and Foreman 1991; Melchor et al. 2002). These phenomena include solution, calcretisation, pedogenesis (forming palaeosols), illuviation, brecciation, and ichnofaunal effects, amongst others. Subaerial diagenetically altered horizons often form a natural capping lithology to regressive carbonate cycles, and in this context, their recognition signals the emergence of a shoaling sequence into the subaerial environment (Read 1973; Goldhammer and Elmore 1984).

Palaeosols are especially important products of subaerially exposed marine carbonate sequences, because they represent the direct surface effects of subaerial diagenesis and pedogenesis, as distinct from more shallowly buried features such as solution (including microkarst) and illuviation, the latter nonetheless still signalling subaerial exposure and subaerial diagenesis. Subaerial disconformities, and palaeosols in particular, have been used as markers to map facies changes in sedimentary sequences and in metamorphic terranes between isochronous 'bounding surfaces' (Semeniuk 1973a; Barrientos and Selverstone 1987). Recognition of palaeosols and their associated ichnofauna, and evidence of plant life also have been central to the reconstruction of geochemistry, hydrochemistry and atmosphere composition of the Precambrian and early Palaeozoic, and when terrestrial environments were first being inhabited [see contrasting interpretations of Precambrian palaeosols by Palmer et al. (1989a, 1989b) and Holland and Feakes (1989), and of Ordovician strata by Retallack and Feakes 1987; Retallack 2001a; and Davies et al. 2010].

The diagenetic and pedogenic effects of subaerial unconformities, with particular emphasis on palaeosols, have been recognised as far back as the Precambrian, and described from a variety of parent rocks, ranging from igneous, metamorphic, sandstones, and carbonate rocks (Wright 1986; Duffin et al. 1989; Retallack and Mindszenty 1994; Retallack 2001b, 2009; Melchor et al. 2002; Jutras et al. 2009). The focus on the more ancient palaeosols from Precambrian to Devonian times has been to determine geochemical changes effected in the weathering materials, provide insight into earlier atmosphere and hydrochemistry in a vegetation-free landscape, to develop criteria to separate pedogenic effects from diagenesis, or to trace the beginnings of plant and animal advance onto the land from the sea (Retallack 1985; Reinhardt and Sigleo 1988). For instance, Jutras et al. (2009) document geochemical features of Ordovician palaeosols to reconstruct climate, content of atmospheric CO_2, groundwater hydrochemistry, and to interpret terrain conditions at the dawn of land plant radiation.

However, while there has been some study of Ordovician palaeosols in carbonate rocks, the focus has been on Ordovician pedogenesis of terrigenous sediments and igneous rocks (Feakes et al. 1989; Driese and Foreman 1991, 1992; Jutras et al. 2009). Few papers have described the effects of subaerial exposure specifically on Ordovician carbonate rocks.

This paper is important, therefore, in that it describes the products of Ordovician subaerial diagenesis and pedogenesis along the subaerial disconformities on varied limestones in the Ordovician Daylesford Limestone (Semeniuk 1973b) at Bowan Park, west of Orange in central western New South Wales, providing details of grains, structures, lithology, and stratigraphy to a level not previously documented regionally or globally. It presents a model of subaerial diagenesis and pedogenesis for Ordovician carbonate rocks and provides indicators for recognising subaerial disconformities in the Ordovician and generally in the geological record.

Semeniuk (1971) described the effects of leaching on these limestones, effectively focusing on the near-surface subterranean effects of subaerial exposure. This paper provides a fuller account of the effects of diagenesis and pedogenesis, with an emphasis on microkarst, internal sedimentation, palaeosols, calcrete, and reworked palaeosols, and on the variable subaerial diagenetic response by the three main parent marine sediments of the sequence, viz., lime mudstone, shelly lime wackestone, and grainstone.

Karst refers to landscape and subterranean structures produced by dissolution of soluble rocks (mainly limestone) that results in large landscape features, dolines, caves, subterranean drainage, and even small-scale features such as pitting, flutes, karren, solution cavities, fossil molds, and bedding plane partings, amongst others (Jennings, 1971, 1985; Sweeting 1972; Bates and Jackson 1987; Ford 1988). The term 'karst' generally has no scale connotations. There have been no large-scale features such as caves, speleothems, dolines, depressions, or cave-fill breccias recorded along the Ordovician subaerial disconformities of the limestones of this study, however, there is a plethora of smaller-scale structural features of dissolution. In this paper, the term 'microkarst' is used to emphasise that there are definitively small-scale products of karst in Ordovician limestone as a result of subaerial exposure and dissolution. Jakucs (1977) uses the term 'microforms' for some features of this scale.

Some explanation of terms is provided here. Diagenesis refers to the alteration of sediments after deposition - it includes solution, cementation, and grain alteration, amongst other effects. In this paper there is focus on sediment alteration that is shallow just below the former subaerial surface. Pedogenesis refers to the alteration of sediments to develop soils – thus, it is a suite of alteration processes that operate from the surface downwards, and its final product is the surface soil. However, as processes, diagenesis and pedogenesis can spatially overlap. The term 'diagenetic sediment' is used herein to refer to the mainly fine-grained sediment that infiltrated the Ordovician sediment or limestone during diagenesis, and partly to fully filled pore space and cavities. It includes the crystal silt of Dunham (1969a), pellets, calcrete-coated and peripherally altered grains, lithoclasts, internally generated "micro-breccias", terrigenous mud, and quartz silt, or can be comprised of mixtures of these materials. Its origin can be internal to the sediment or rock, or illuvial (illuvium being the material transported down a soil profile usually from the surface by the action of rainwater). Generally, diagenetic sediment is fine-grained (i.e., silt to very fine sand-sized), but locally some lithoclasts within cavities are up to medium sand-size. A ped is a unit of soil structure, such as an aggregate, crumb, prism, block, or granule, formed by natural processes and, as such, soils with ped structure commonly have interconnected inter-ped spaces.

The limestone classification of Dunham (1962) is used in this paper. Based on depositional fabric, Dunham (1962) recognised six types of limestone, four of which are relevant here: 1. lime grainstone (equivalent to calcareous sand and gravel deposits); 2. lime packstone (equivalent to calcareous muddy sand and gravel deposits); 3. lime wackestone (equivalent to calcareous sandy and gravelly lime mud deposits); and 4. lime mudstone (equivalent to calcareous mud deposits). Since the majority of sediments in this study are limestones, the terms of Dunham (1962) are generally shortened to grainstone, packstone, wackestone and mudstone to refer to the four depositional categories, and the adjectival descriptor 'skeletal', or 'lithoclastic' is used to refer to the calcareous sand or gravel grains that comprise the grainstone, packstone, or wackestone. The general term 'muddy limestone' refers to all limestones that formerly were composed totally or partly of calcareous mud (and hence refers to lime packstones, lime wackestones and lime mudstones). Distinguished from the muddy limestones is a small proportion of terrigenous mudstone in the Daylesford Limestone, that can be sedimentary or pedogenic in origin.

Fine-grained calcite has been described in this paper in terms of grainsize as cryptocrystalline (crystals < 1 µm), and microcrystalline (crystals 1 µm to 10 µm) (Folk 1959; Bissell and Chillingar 1967; Bathurst 1975). In the patches of fine-grained calcite (formerly either sedimentary lime mudstone or calcrete patches), the fine-grained mosaics are inter-gradational because of recrystallisation. Cryptocrystalline calcite can be recrystallised to microcrystalline calcite. Interstitial pores, or interstices, in formerly calcareous sand, can be filled with cryptocrystalline and/or microcrystalline calcite, and the grains of the sand can be recrystallised to cryptocrystalline and/or microcrystalline calcite. Consequently, there is not a sharp distinction made in this paper between cryptocrystalline and microcrystalline.

The study is based on field sites, stratigraphy along five transects, and on 470 samples, the latter examined mainly in thin section and as polished slabs. Staining methods of Friedman (1959) and X-Ray Diffraction (XRD) were used to distinguish calcite from dolomite, and quantitative XRD was used to determine the content of pyrite and Fe-oxides. Scanning Electron Microscopy (SEM) was used to investigate fine-grained crystal textures, and Electron Dissipative Spectroscopy (EDS) was used to determine element distribution and mineral phases, especially of Fe and Mn minerals at the micron-scale. Numbers prefixed USGD and SUP refer to specimens formerly catalogued in the petrology and palaeontology sections, respectively, of the Department of Geology and Geophysics, University of Sydney and now housed at the Geological Survey of New South Wales at Londonderry, NSW.

PROCESSES AND PRODUCTS ALONG SUBAERIAL DISCONFORMITIES – A BRIEF REVIEW AS BACKGROUND TO INTERPRETING ORDOVICIAN SUBAERIAL EXPOSURE

The processes and products operating along and developed on subaerial disconformities on marine carbonate sediments of Holocene, Pleistocene, and pre-Quaternary carbonate rocks in various climatic settings are well documented (Fairbridge and Teichert 1953; Friedman 1964; Gile et al. 1966; Roehl 1967; Matthews 1967, 1968; Purdy 1968; Dunham 1969a, 1969b; Kendall 1969; Land 1970; Reeves 1970; Semeniuk 1971; Chafetz 1972; Purser 1973; Brown and Woods 1974; Logan 1974; Read 1974; Braithwaite 1975; Read and Grover 1977; Videtich and Mathews 1980; Esteban and Klappa 1983; Esteban and Pray 1983; Goldhammer and Elmore 1984; Harris et al. 1985; Francis 1986; Wright 1986; Brewer and Sleeman 1988; Ford 1988; Tucker and Wright 1990; Wright and Tucker 1991; and Melchor et al. 2002). There are also many processes and products resulting from subaerial exposure, weathering, and pedogenesis of other rock types from a range of geological ages that nevertheless are universal and applicable also to carbonate rocks, e.g., root-structuring, humification, illuviation, geochemical alteration (Retallack 1985, 2001b, 2009; Wright 1986; Reinhardt and Sigleo 1988; Feakes et al. 1989; Holland and Feakes 1989; Palmer et al. 1989a, 1989b; Driese and Foreman 1991; Retallack and Mindszeny 1994; Jutras et al. 2009). Similarly, texts such as Buol et al. (1973), FitzPatrick (1983), Wilding et al (1983), Brewer and Sleeman (1988), and Leeper and Uren (1993), refer to the general principles of alteration and pedogenesis involved in subaerial environments, and provide principles and processes in pedogenesis that are applicable to interpreting subaerial diagenetic and pedogenetic effects in carbonate rocks.

However, depending on climate (in particular rainfall), and the parent material and its geochemical lability, subaerial exposure will generate various products. The literature on palaeosols and weathering, and effects of subaerial exposure from modern and/or ancient sequences should be carefully applied to interpret those rocks and sediments of different petrology, different climate environment, or different landscape and hydrological setting. At best, the descriptions of subaerially altered materials and ancient palaeosols serve to show firstly, that there was subaerial exposure in a given geological age, secondly, that there are some consistently developed products that can signal environmental setting (e.g., plant roots), thirdly, the potential geochemical and hydrochemical processes and products that can derive from subaerial exposure, and fourthly, the nature of the environment in which the alteration took place in terms of its climate, landscape, hydrology, and biology. As such, granites, basalts, sandstones, shales, and carbonate rocks and carbonate sediments may respond differently, and some of the criteria developed to identify subaerial exposure and weathering in one suite of materials cannot always be applied to another. For this paper, a summary of the literature cited above will focus on the effects of subaerial exposure and pedogenesis on carbonate rocks and carbonate sediments, and those aspects of subaerial alteration and pedogenesis derived from other materials that *can* be applied to carbonate rocks.

For carbonate sediments and rocks, it is also important to separate pedogenesis and subaerial diagenetic effects on unlithified marine carbonate sediments from those that are weakly cemented or fully indurated to limestone. At one extreme, there would be a suite of metastable grains of varying carbonate composition, and material that is permeable to groundwater and vadose water, and hence subject to particular pathways of pedogenesis and diagenesis. At the other extreme, there would be indurated and relatively impermeable materials that would be subject more to karst processes.

Diagenetic effects on unlithified to weakly cemented marine carbonate sediments beneath and at subaerial disconformities at local to regional scale are characterised by (Dunham 1969a; Land 1970; Bathurst 1975; Esteban and Klappa 1983; Wright and Tucker 1991):

1. root features;
2. ped development;
3. humification at the surface;
4. illuviation of fine-grained sediment (mainly crystal silt of Dunham 1969a);
5. illuviation of exotic sediment (such as aeolian dust);
6. geochemical alteration and adjustments from the surface downwards;
7. development of a K-horizon or some form of hardpan in the shallow subsurface;
8. specific types of geochemical effects at the water table (e.g., Fe precipitation);
9. pitting and whole-scale solution of selected grains (e.g., aragonite shells);
10. disaggregation of polymineralic and/or multi-textured skeletons to form internal sediment;
11. fossil molds and solution cavities (if the sediment is weakly coherent or cemented);
12. small- to large-scale depressions, cracks, fissures, and irregular surfaces;
13. erosional surfaces at the disconformity with truncation of structural and petrographic features at the disconformity;
14. regional erosional pinch-out of beds;
15. iron-staining of disconformity surfaces; and
16. silicification, including silicification of fossils.

Indurated marine carbonate sediments (limestones) beneath and at subaerial disconformities at local to regional scale are characterised by:

1. microkarst and macrokarst features;
2. fossil molds and irregular solution cavities, commonly with internal sediment (mainly crystal silt of Dunham 1969a);
3. small- to large-scale depressions, cracks, fissures, and irregular surfaces filled with marine sediment or soil;
4. fracture and veining;
5. illuviation of fine-grained sediment (mainly crystal silt of Dunham 1969a);
6. illuviation of exotic sediment (such as aeolian dust);
7. geochemical alteration and adjustments from the surface downwards;
8. erosional surfaces at the disconformity with truncation of structural, fossil, and petrographic features at the disconformity;
9. regional erosional pinch-out of beds;
10. iron-oxide staining of disconformity surfaces; and
11. silicification, including silicification of fossils.

There is a wider range of effects in uncemented marine sediments because they tend to be geochemically more diverse than limestones (Bathurst 1975), and hydrologically more porous and permeable.

Evidence of a disconformity in overlying units includes:

1. palaeosols;
2. surface residues of leaching (e.g., clay mineral or quartz silt residue);
3. lithoclasts and grains coated by cryptocrystalline calcite (calcrete-ooids of Read 1974) which represent reworked palaeosols;
4. marine sediments containing abundant grains coated, and peripherally replaced by cryptocrystalline calcite and representing reworked soils;
5. abundant gravel- and sand-sized lithoclasts in the marine limestone immediately above the disconformity;
6. remanié fossils (reworked fossils) in the marine limestone immediately above the disconformity;
7. abrupt lithology changes that are unrelated to underlying facies; and
8. organic encrustations (such as corals and stromatoporoids) and borings either on erosionally-planed, sparry calcite-cemented grainstone or on brittle muddy limestones.

Major disconformities with their associated diagenetic alteration can be recognised regionally. Minor disconformities may be of local significance, and associated with less intense alteration. That is, some disconformities were not major events and the subaerial alteration associated with them was not consistently developed regionally.

GEOLOGIC SETTING OF THE DAYLESFORD LIMESTONE

The Ordovician Daylesford Limestone (Semeniuk 1973b) is the basal formation of the Bowan Park Group, which crops out in central western New South Wales (Fig. 1). The Daylesford Limestone disconformably overlies the Cargo Volcanics and is disconformably overlain by Quondong Limestone. At its type section, the formation is 250 m thick and contains six members which in ascending order are: 1. Ranch Member; 2. Bourimbla Limestone Member; 3. Manooka Limestone Member; 4. Gerybong Limestone Member; 5. Glenrae Limestone Member; and 6. Davys Plains Limestone Member. The Oakley Limestone Member is laterally equivalent to Manooka and Gerybong Limestone Members to the east and occurs between Bourimbla and Glenrae Limestone Members. Table 1 summarises lithologies and stratigraphic relationships of the members.

The focus of this paper is on the Ranch Member, Bourimbla Limestone Member, Manooka Limestone Member, Gerybong Limestone Member, Glenrae Limestone Member, and the Oakley Limestone Member, where disconformities are well marked and separate distinct sedimentation phases. At the top of the Glenrae Limestone Member is a major disconformity above which occurs the Davys Plains Limestone Member (which contains skeletal lithoclast grainstone, pisolitic lithoclast grainstone, dark grey skeletal packstone and wackestone, pellet packstone). The Davys Plains Limestone Member contains numerous disconformities and records a phase of the history of the Daylesford Limestone wherein there was much subaerial exposure and reworking. This topmost unit of the Daylesford Limestone is overlain disconformably by the Quondong Limestone (Semeniuk 1973b).

The Daylesford Limestone consists mainly of four broad limestone types which are: 1. grainstone; 2. skeletal wackestone and packstone; 3. burrowed wackestone and packstone; and 4. burrowed lime mudstone. The limestones strike approximately east-west for 9 km permitting analysis of facies changes in

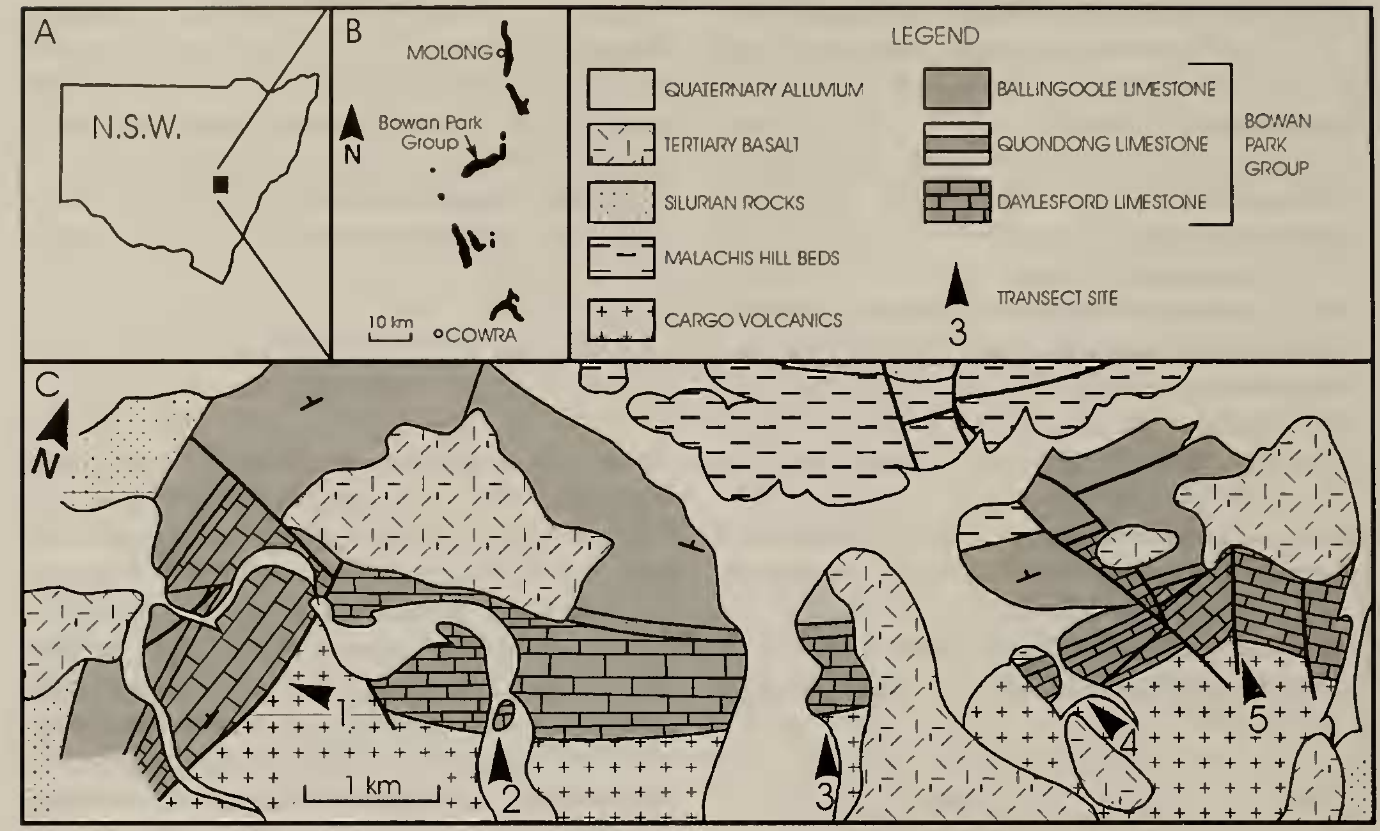
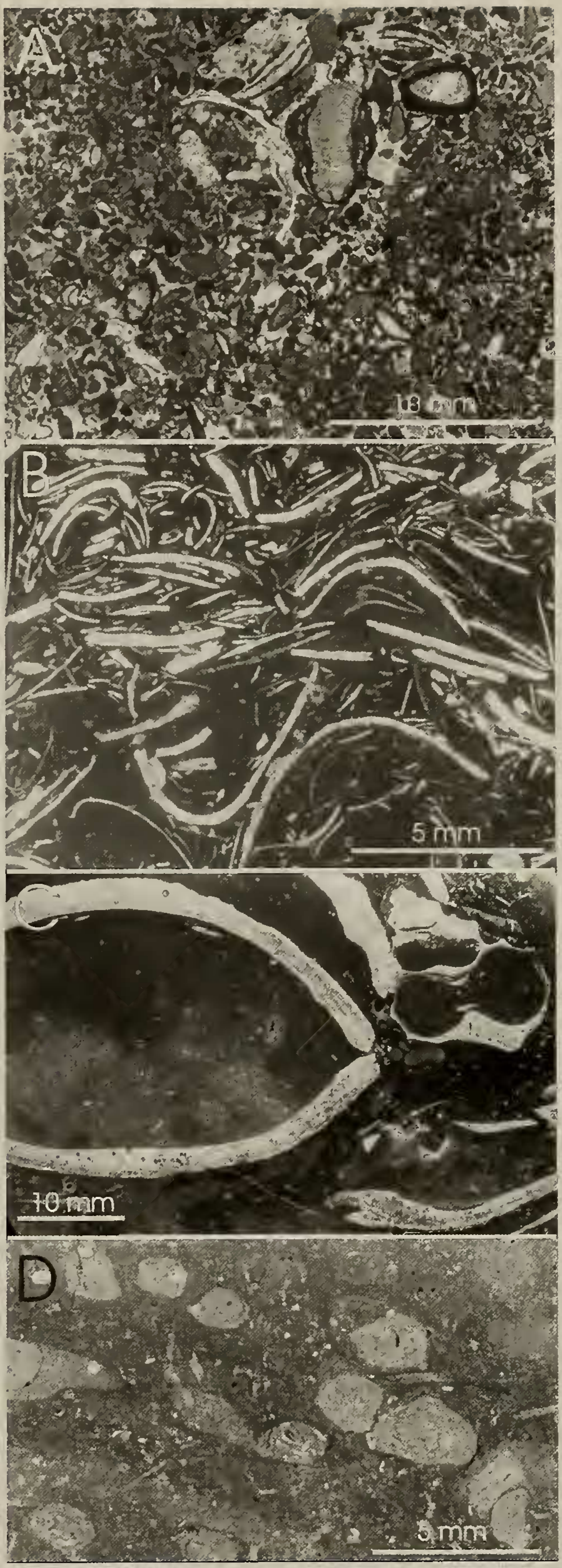


Figure 1. Simplified geological map of the Bowan Park area showing distribution of the Daylesford Limestone (after Semeniuk 1973a, 1973b), and location of the stratigraphic transects.

Western localities	Eastern localities
Davys Plains Limestone Member (95 m thick): interbedded massive skeletal lithoclast grainstone, pisolitic lithoclast grainstone, dark grey skeletal packstone and wackestone, pellet packstone; disconformably overlain by Quondong Limestone and disconformably overlies:	
Glenrae Limestone Member (25 m thick): in western localities consists of intercalated and burrow-mottled grainstone, skeletal wackestone and lime mudstone in lower part and massive light grey mottled limestone in upper part; in eastern localities consists of massive light grey mottled limestone; overlies and grades into:	
Gerybong Limestone Member (64 m thick): intercalated, thinly bedded dark grey lime mudstone and skeletal wackestone; conformably overlies:	**Oakley Limestone Member** (90 m thick): massive skeletal grainstone and skeletal lithoclast grainstone.
Manooka Limestone Member (16 m thick): skeletal lithoclast grainstone, skeletal grainstone, dark grey skeletal packstone, wackestone, lime mudstone; disconformably overlies:	
Bourimbla Limestone Member (24 m maximum thickness): thinly to massively bedded grey skeletal wackestone and packstone, dark grey skeletal wackestone, lime mudstone; disconformably overlies:	
Ranch Member (34 m thick): mainly thinly bedded marl, terrigenous mudstone and, towards base, lithic sandstone and mudstone; disconformably overlies Cargo Volcanics	

Table 1: Stratigraphy and lithologies of the Daylesford Limestone

Figure 2 RIGHT. Thin sections of parent limestones in the Daylesford Limestone. A. Skeletal grainstone, from the Manooka Limestone Member, composed dominantly of crinoid ossicles, and subordinate mollusc and coral fragments (USGD 46711). B. Skeletal packstone, from the Ranch Member, composed dominantly of molluscs (USGD 46673). C. Skeletal wackestone, from the Bourimbla Limestone Member, composed of gastropods and the brachiopod Eodinobolus (USGD 46651). D. Burrowed lime mudstone, from the Ranch Member (USGD 47034).



a direction perpendicular to the original Ordovician shoreline (Semeniuk 1973a). Grainstone and skeletal wackestone and packstone dominate eastern sections of the Formation; they are laterally equivalent to, and interfinger with, muddy limestone that dominates western sections (Semeniuk 1973a). Lithoclasts occur in the grainstones but are absent from muddy sections to the west, except in thin horizons above disconformities.

In more lithologic detail, host limestones beneath subaerial disconformities include lithoclast and skeletal grainstones and muddy limestones (Semeniuk 1973a). Grainstones are medium to coarse sand-sized sediments, composed of skeletons (mostly calcareous algae, echinoderms, and molluscs) and lithoclasts with layers of gravel-sized fossils, lithoclasts, and *Girvanella* nodules; grainstones are cemented by sparry calcite. Muddy limestones include skeletal wackestones and packstones, and lime mudstones. Skeletal wackestone and packstones tend to be dark grey and contain sand- and gravel-sized whole and fragmented fossils in a lime mud matrix; some sediments contain abundant pellets. Once accumulated, under the low energy conditions of their depositional environment, they remained anoxic. Large fossils include brachiopods, molluscs, stromatoporoids, corals and calcareous algae; these are oriented and in layers, or randomly oriented and disrupted by burrows. The matrix is lime mud containing abundant, poorly sorted, angular, fine to coarse sand-sized skeletal fragments, particularly if the sediments are burrowed. Skeletal fragments in the lime mud matrix include thin-shelled brachiopods, sponge spicules, dasycladacean algae, ostracods, trilobites, bryozoans, and small gastropods. Lime mudstones tend to be dark grey, commonly burrowed, and composed of cryptocrystalline calcite, patches of microcrystalline calcite, and < 10% silt- to sand-sized skeletal fragments similar to those in the matrix of skeletal wackestones and packstones. Intraskeletal voids of fossils in muddy limestones are filled with sparry calcite. As with the packstones and wackestones, once accumulated, under the low energy conditions of their depositional environment, they remained anoxic.

A range of the primary lithologies of the Daylesford Limestone are illustrated in Figure 2 to provide a baseline of limestone types that are host to the Ordovician subaerial diagenesis. These range from grainstone to lime mudstone, and show relatively intact fabrics of grains, cements, lime mud fabrics, and well preserved fossil material.

Numerous subaerial disconformities occur within many limestone members and separate major sedimentological phases in the Daylesford Limestone. The disconformities converge eastwards and cause wedging-out of units indicating that, during deposition, the Daylesford Limestone was flanking an axis to the east known as the Molong Volcanic Belt. For a history of the nomenclature of this axis see Packham (1969), Gilligan and Scheibner (1978), Packham et al. (2003), Gray and Foster (2004), Glen et al. (2007), and Percival and Glen (2007). The significant features of this axis are that deposition of the Daylesford Limestone took place on its western flank, and consequently in eastern parts of the Daylesford Limestone during times of subaerial exposure, with any relative change in sea level in the Ordovician, there was enough relief for limestones to be subaerially eroded and reworked as lithoclasts into the depositional basin to the west (Semeniuk 1973a). In this palaeogeographic setting, grainstone, grey skeletal wackestone and packstone accumulated in nearshore environments nearest to the axis of the Molong Volcanic Belt as suggested by their stratigraphic position and abundant lithoclasts, and by their association with desiccated sediments. Dark grey lime mudstone formed in offshore, low-energy environments further to the west, as suggested by their stratigraphic location, abundance of lime mud and lack of shallow-water indicators. Dark grey wackestone and packstone formed in intermediate environments. Burrowing organisms locally produced burrow-mottled limestone or mixed, interbedded grainstone and muddy limestone.

Prior to describing and assigning early diagenetic/pedogenetic effects to subaerial disconformities in the Ordovician limestones, it is necessary to describe the products of later diagenesis and low grade regional metamorphism (cf. Ryall 1965; Smith 1968) to separate their effects from subaerial effects. This is important because the subaerial diagenesis/pedogenesis in the Daylesford Limestone is Ordovician in age and sets a standard of such alteration in marine carbonate sediments that is not well described globally, and thus needs to be clearly viewed through and separated from later overprints.

Given the limited mineralogy of the Ordovician limestones (i.e., calcite, and silica) and their labile nature, alteration deriving from later diagenetic and low grade regional metamorphic processes may overlap in time and in products. Late diagenesis and low grade regional metamorphism resulted in recrystallisation of microcrystalline and cryptocrystalline calcite to coarser crystal fabrics, recrystallisation of sparry calcite to coarse textures and blocky calcite, twinning of calcite, intergranular suturing of calcite crystal mosaics, development of triple junction interfaces in calcite crystal mosaics, dolomitisation, fluorite replacement of calcite, gypsum precipitation and its later calcitisation, stylolite development, brittle fracturing and cavity filling (i.e., calcite veining), and some silicification. This later diagenesis and low grade metamorphism in fact overprints the products of diagenesis and pedogenesis associated with subaerial esposure.

DIAGENETIC EFFECTS ASSOCIATED WITH SUBAERIAL DISCONFORMITY SURFACES IN THE DAYLESFORD LIMESTONE

Limestone are described in increasing scale from grains, fabrics and structures, building up to lithologies, and then stratigraphic profiles. The products of Ordovician subaerial exposure are described in increasing scale because the recognition of subaerial surfaces is very important in ancient sequences dating as far back as the Ordovician. Given that descriptions of Ordovician subaerial diagenesis and pedogenesis are rare globally, all components of the alteration associated with subaerial exposure in the Daylesford Limestone need to be individually addressed and described: from grains that are developed under, at, or above disconformities, to the fully developed palaeosols or microkarst features where the entire suite of grains and minerals, fabrics and structures, and lithologies are preserved in context. In this scalar framework, the signal that there has been subaerial exposure of marine sediments can be reconstructed at one extreme, in the best preserved situations, from fully developed profiles to an intermediate situation where there is only a portion of the profile (if eroded during the Ordovician, or later faulted or metamorphosed), to the other extreme, in the least preserved situation, where the only evidence of subaerial exposure are grains derived from subaerial profiles that have been reworked into the next cycle of marine sediments.

Grains and minerals, fabrics and structures, and lithologies associated with disconformities include: 1. (for grains and minerals) lithoclasts, calcrete-coated and peripherally-altered lithoclasts, remanié fossils, internal sediments, terrigenous mud, and silica; 2. (for fabrics and structures) fossil molds, enlarged fossil molds, cavities, mottles, fissures and irregular surfaces, patches of cryptocrystalline and microcrystalline calcite, and bleaching; and 3. (for lithologies) vugular limestone, mottled limestone, massive light grey limestone, lithoclast grainstone, calcrete-ooid grainstone, calcrete-ooid packstone and wackestone, pellet packstone and wackestone, (terrigenous) mudstone, and palaeosols.

GRAINS AND MINERALS

Lithoclasts

Lithoclasts are sand- and gravel-sized carbonate rock fragments eroded from older lithified carbonate rocks beneath disconformities (Folk 1959). In the Daylesford Limestone, lithoclasts include fragments of lime mudstone, skeletal, pelletal, and lithoclast wackestone, packstone, and grainstone (Fig. 3A), calcrete-cemented grainstone, laminar calcrete (Fig. 3B), veined laminar calcrete, and reworked fossil casts of 'steinkerns' (Fig. 3C). Lithoclasts are recognised by drusy and blocky calcite internal cements, solution textures, calcite veins, limonite pigments, silica-replacement textures, and recrystallisation textures within the grain; grain boundaries truncate these internal diagenetic fabrics.

Calcrete-ooids

Many sand-sized lithoclasts in the Daylesford Limestone are superficially coated by concentrically laminated envelopes of cryptocrystalline calcite (Figs 3D and 3E). The envelopes are commonly asymmetrically concentrically laminated. There are internal micro-unconformities within the lamination of the ooids, and these are commonly pigmented by limonite. They are comparable to Quaternary calcrete-ooids formed by soil processes (see Fig. 3F; and Read 1974), both in terms of morphology and limonite pigmentation. They are also termed 'vadoids' by Peryt (1983), to refer to coated grains formed in the vadose zone. The calcrete-ooid envelopes (simple, cryptocrystalline, free-grain cutan or calcitan of Brewer 1964) have sharp contacts with the grain and are commonly asymmetrical. They are readily distinguished from marine ooids: the former composed of asymmetric concentric envelopes of fine-grained equant calcite, with internal Fe-oxide rinds marking micro-unconformities; the latter having a strong symmetric concentric structure of tangentially aligned carbonate crystals or (for recrystallised ooids) strong radial array of carbonate crystals (Bathurst 1972).

The coats are mostly developed on lithoclasts and some remanié fossils. In contrast, fossils and fossil fragments that are autochthonous within a bed are uncoated, or algal-micrite coated and bored. The absence of both tubules and penetrating contacts distinguishes these surficial calcrete envelopes from algal-micrite envelopes produced by algal borings (Bathurst 1966; Logan 1974).

Some of the calcrete-coated grains are gravel-sized and would be termed calcrete pisolites. However, they are not common as a grain type. Moreover, the calcrete coating on the gravel-sized grains are thin, not like the thickly and multiply coated pisolites of the Guadalupe Mountains (Kendall 1969) and Shark Bay (Read 1974). Figure 3G shows a *Girvanella* nodule to contrast the internal laminar structure of these algal concretions with calcrete ooids.

Peripherally-altered lithoclasts

Lithoclasts may also be peripherally altered with a cryptocrystalline calcite rind that is gradational into the unaltered core of the grain (Fig. 3H). The alteration is most evident in clasts comprised of grainstone or packstone. Alteration is most complete in outer portions of rinds and inner portions commonly retain relict limestone textures (Fig. 3H). Alteration zones range from thin veneers (0.1 mm) to thick rinds (10 mm) that are up to half the grain radius. Some rinds are limonite-stained. The association of cryptocrystalline calcite rinds with lithoclasts, calcrete-coated lithoclasts, and limonite-pigmented grains indicates that they are the weathered margins of grains. Similar cryptocrystalline rinds around carbonate grains occur in modern calcareous soils (Read 1974), where microsolution and precipitation of calcium carbonate occurs on outer portions of grains. The rinds are distinguished from algal micrite envelopes (Bathurst 1975) by their gradational contact with the parent grain, pigmentation, and lack of (tubular) penetrative contact with the unaltered core.

Remanié fossils

Remanié fossils are skeletons as free fossil grains reworked from previously deposited sediments or rocks (Fig. 4). To some extent, remanié fossils grade into lithoclasts and calcrete-ooids in that they commonly have some adhering matrix, or may be coated by calcrete envelopes. Hollow skeletons such as gastropods and *Tetradium* tubules exemplify this as they have marine mud as internal sediment and, as such, when reworked, this sediment forms the majority of the reworked mass. Grains that are thinly coated by calcrete, and those that have a minority of externally adhering matrix are assigned to remanié fossils, while those with thick envelopes of calcrete, or where the fossil is a minor component of the rock-fragment grain are assigned to calcrete-ooids and

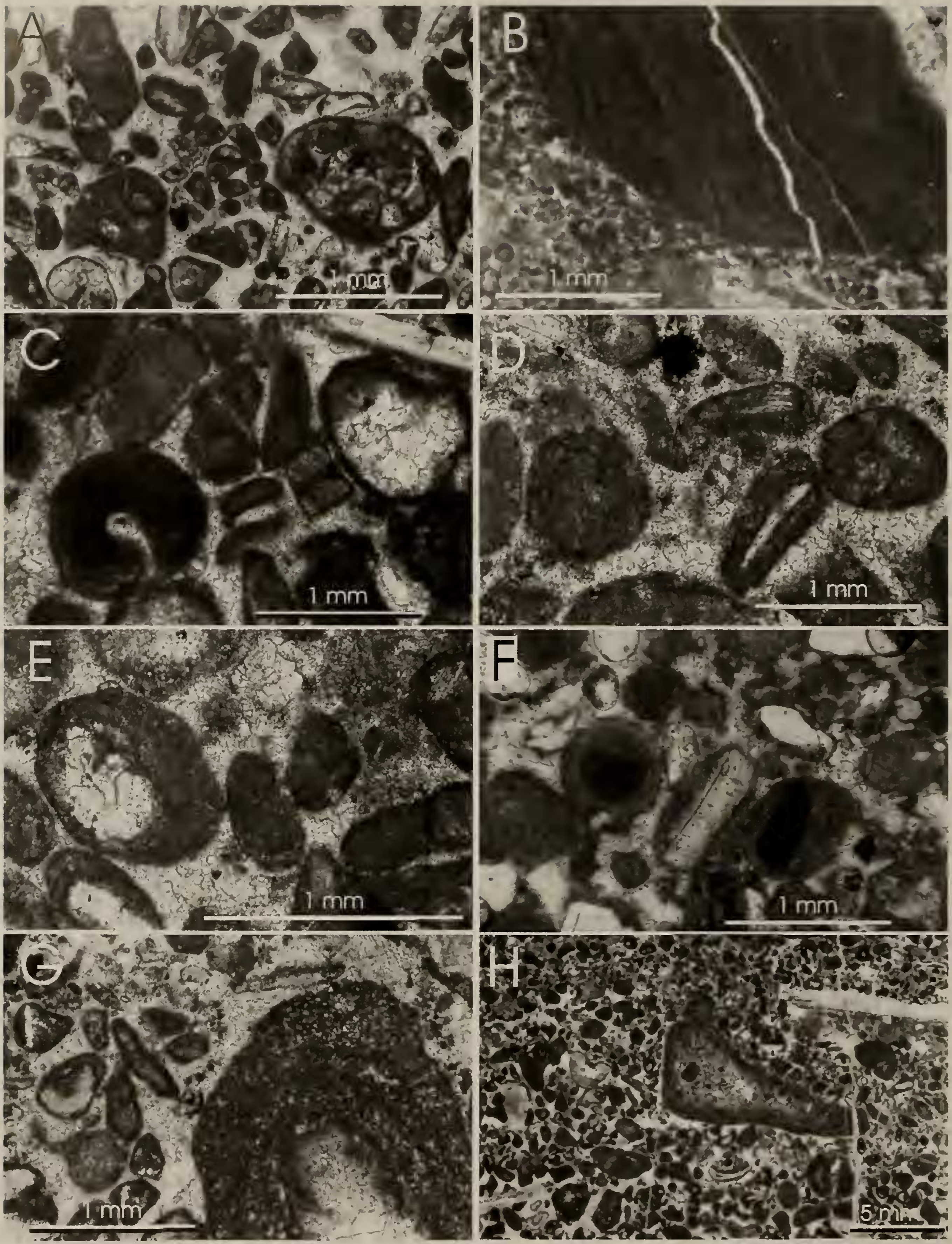

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Figure 3 LEFT. Thin sections of grains that are products of subaerial exposure. A. Lithoclasts in a grainstone (Davys Plains Limestone Member; USGD 47040). B. Rounded lithoclast of laminar calcrete, showing laminae parallel cracking (now veins; probably crystallaria of Wright and Tucker 1991), reworked into the overlying Quondong Limestone from the disconformity at the top of the Glenrae Limestone Member (USGD 42144). C. Steinkern (internal gastropod cast) and lithoclasts from the Manooka Limestone Member (USGD 46711). D. Calcrete ooids in a grainstone (Davys Plains Limestone Member) showing concentric lamination; laminae are highlighted by limonite staining (USGD 41815). E. Close-up of calcrete ooids showing details of ooid laminae (Davys Plains Limestone Member; USGD 41815). F. Calcrete ooids from the Quaternary of Shark Bay for comparison with (C) and (D). G. Girvanella nodule showing lamination, tubules, and spongy internal fabric from the Davys Plains Limestone Member to contrast with the calcrete ooids (USGD 47041). H. Peripherally altered lithoclast in the Davys Plains Limestone Member (USGD 47036).

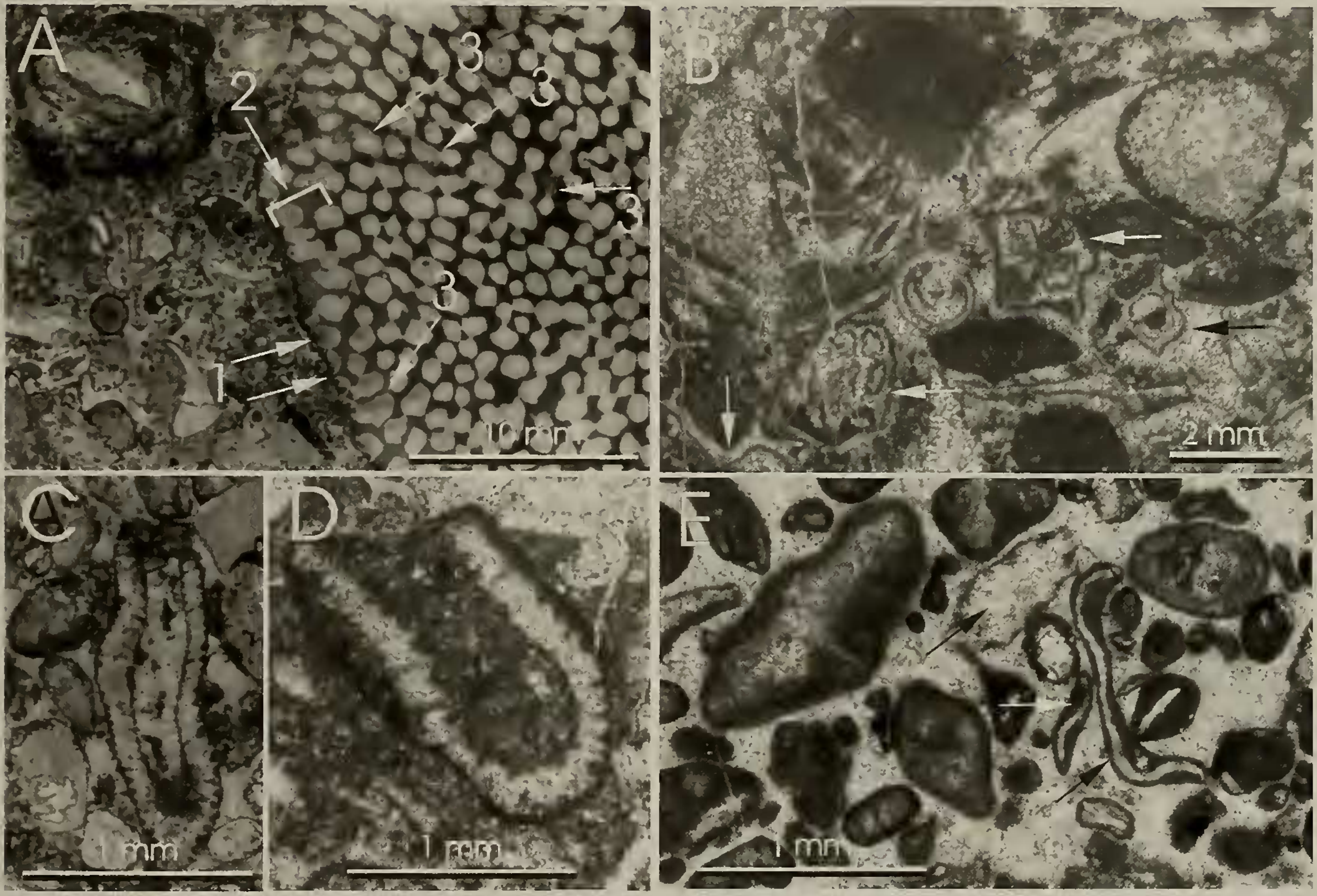


Figure 4. Thin sections of remanié fossils. A. Reworked gravel-sized clast of Tetradium in grainstone. This remanié fossil shows mud between the tubules. The exterior of the clast is limonite stained (arrow 1). The interior of the clast is dark grey lime mudstone, while the exterior rind is bleached lighter grey (arrow 2). The Tetradium is leached, and while most of the skeletal molds have been filled with sparry calcite that is truncated by the clast boundary, some of the skeletal molds are partially filled with diagenetic sediment (arrow 3). B. Broken Tetradium tubules as remanié fossils (arrowed) in a lithoclastic grainstone; some of these remanié fossils exhibit lime mud in the skeletal cavity, as it typical of the Tetradium lithosome. C. Vermiporella fragment in a grainstone for contrast with the remanié fossil to be shown in (D); USGD 46703. D. Vermiporella reworked from a skeletal packstone, occurring as a remanié fossil; the interior of the fossil is lime mud (USGD 46704). E. Remanié fossils of ostracods, coral fragments, brachiopods, and molluscs (three are arrowed); most of the fossils are lightly to more thickly coated by calcrete envelopes (USGD 41814).

lithoclasts, respectively. In the Daylesford Limestone remanié fossils occur in soils or are mixed with marine sediments above disconformities. Remanié fossils are readily detected where they occur either as exotic, silicified fossils in palaeosols and sediments which overlie skeletal limestones containing similar fossils autochthonously, or in lithoclastic grainstones as fossils that are exotic to the skeletal assemblage of the host sediment. The latter remanié fossils either occur elsewhere autochthonously in muddy rocks (e.g., *Tetradium* colonies now embedded in grainstone), or are part of a similar skeletal assemblage to those in lithoclasts. Skeletons, such as the *Tetradium* mentioned above, if exotic in lithoclastic grainstones commonly have mud-filled, inter- and intra-skeletal voids or diagenetic textures (internal cements, leached cavities with internal sediment) that are truncated by the grain boundary (Figs 4A and 4B).

Reworked algal (*Girvanella*) nodules also can be remanié fossils. Remanié algal nodules, in contrast to the spongy internal texture and sparry calcite-filled tubules, that *Girvanella* nodules exhibit in their autochthonous settings, are partly to completely impregnated with cryptocrystalline (and microcrystalline) calcite, though *Girvanella* tubules are still recognisable. Some remanié nodules also have patches of cemented limestone attached to their margin. These types of remanié *Girvanella* nodules appear to have been calcrete-impregnated and/or calcrete-altered when the *Girvanella*–bearing limestone was subaerially exposed.

Diagenetic sediment, including illuvium

Diagenetic sediment is used as a term here to refer to that sediment that has infiltrated into the sediment or rock profile during diagenesis (Fig. 5). Some of this sediment had been generated within the sediment and/or rock profile (e.g., crystal silt of Dunham [1969a], pellets, lithoclasts). Exotic sediment, such as aeolian dust, and other forms of fine-grained sediment generated on the subaerial surface and washed into the sediment/rock profile is termed illuvium (this includes pellets, calcrete-coated and peripherally altered grains, lithoclasts, terrigenous mud, and quartz silt that formerly were on the disconformity surface). Diagenetic sediment partly to completely fills intergranular voids, fossil molds, irregular solution cavities and fractures (Fig. 5). Crystal silt (Dunham 1969a) is the most common internal sediment. It is a well-sorted accumulation of silt-sized calcite crystals (0.01 mm to 0.03 mm in size) and is commonly light grey in tone. Some crystal silt, mixed with terrigenous clay and quartz silt (i.e., crystal silt mixed with exotic fine-grained illuvium), forms brown internal sediment. Pellets and sand-sized grains are less common as a constituent of internal sediment and illuvium, and are mixed with crystal silt. Pellets are angular to round aggregates (0.05 mm to 0.2 mm in size) of cryptocrystalline calcite. Lithoclasts are sand-sized grains of cryptocrystalline calcite. Locally, collapse of solution cavities produces a micro-breccia.

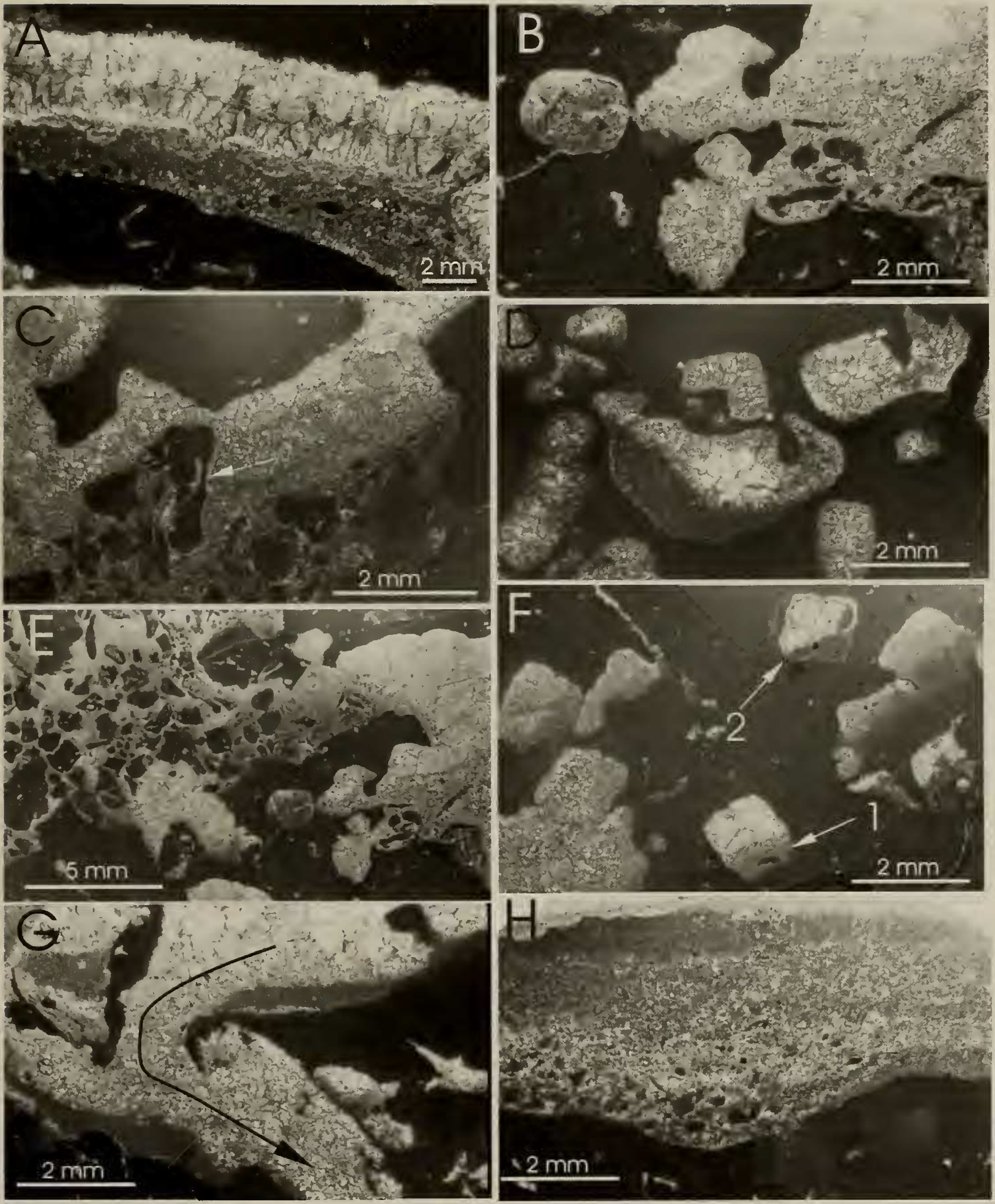
Terrigenous mud

Locally, either as a bed, or mixed with the internal sediment as described above, there is terrigenous mud composed of terrigenous clay, fine-grained mica, and quartz silt.

Silica

Fossils and sparry calcite are replaced by silica beneath some disconformities. Replacement silica is a mixture of chalcedony and equant quartz (average size 0.03 mm). Original fibrous nature of skeletons

Figure 5 RIGHT. Thin sections of diagenetic sediment. A. Crystal silt and pellets partially filling an Eodinobolus mold (USGD 46641). B. Diagenetic sediment of crystal silt, pellets and lithoclasts partially filling Tetradium molds (USGD 46643). C. Layered and graded deposit of diagenetic sediment, with coarse lithoclasts, finer lithoclasts, and crystal silt; lithoclasts produced by wall collapse; Tetradium fragment in one of the lithoclasts is arrowed (USGD 46643). D. Diagenetic sediment filling cavities derived by dissolution of Tetradium; the large central cavity is an enlarged Tetradium mold with crystal silt resting directly on the cavity floor. E. Micro-breccia of lithoclasts formed by collapse of walls and roof of solution-enlarged Tetradium molds; the square cross-sectional shape of Tetradium is still evident in many of the molds (USGD 46641). F. Contrast in sediment-fill in Tetradium cavities; arrow 1 shows diagenetic sediment of crystal silt and pellets in a mold, with diagenetic sediment resting directly on the floor of the mold arrow 2 shows lime mud on the inside wall of the Tetradium tubules and the colour and texture of the mud is the same as the sedimentary matrix surrounding the corallites. G. Diagenetic sediment deposited on the floors of inter-connected enlarged (Tetradium mold) vughs; the diagenetic sediment, as crystal silt, has cascaded gravitationally along the vugh network (one pathway is shown by the arrow); USGD 46658). H. Granulometrically graded, and laminated diagenetic sediment in a solution cavity, with lithoclasts and pellets towards the base, and crystal silt in the upper part (USGD 47037).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is obliterated and replaced with radiating bundles of silica fibres or equant silica grains, or both. Where silica replaces sparry calcite, it may pseudomorph the carbonate crystal habit. (The origin of diagenetic silica and metamorphic silica is discussed later).

FABRICS AND STRUCTURES

The fabrics and structures associated with subaerial disconformities include fossil molds, enlarged fossil molds, cavities, mottles, fissures and irregular surfaces, cryptocrystalline (and microcrystalline) calcite patches and bleaching.

Fossil molds, enlarged fossil molds, cavities and mottles

Fossil molds, enlarged fossil molds, cavities and mottles are intergradational (Fig. 6). Selective leaching of fossils, particularly in wackestones and packstones, forms fossil molds. At this stage of solution, the fossil shapes are clearly evident, viz., the shapes of *Tetradium* (a tubular skeleton), *Eodinobolus* (a brachiopod), or *Alleynodictyon* (a cylindrical stromatoporoid). At the next stage, where fossil molds are enlarged by solution, part of the cavity is still discernable as to fossil origin (and species origin). Some of these enlarged fossil molds are further enlarged by solution, and form interconnecting and irregular cavities in the host sediment. Thus, there is an intergradational and interconnecting range of structures from molds, enlarged fossil molds, and irregular cavities.

Subsequent filling of cavities with a mosaic of calcite and/or diagenetic sediment of crystal silt, pellets, calcrete-coated and peripherally altered grains, or lithoclasts has formed: 1. fossil casts in limestone in which leached fossil molds have been filled with sparry calcite and internal sediment (crystal silt, some pellets, and lesser amounts of lithoclasts); 2. interconnecting spar-filled vughs; 3. mottled limestone with cavities and fractures filled, partly or completely, with internal sediment; and 4. '*Stromatactis*' structures composed of enlarged fossil molds with irregular roofs, flat floors of crystal silt and remaining fill of sparry calcite. Where partially filled by internal sediment, the internal sediment is geopetal. Where fully filled by internal sediment, the fossil molds become casts of internal sediment. Where interconnecting and irregular cavities are filled with internal sediment, the former shelly or fossiliferous limestone becomes mottled limestone. Often there is intergradation between fossil, solution-enlarged fossil shapes, and mottled limestone that shows the relationship in the fabric and structure types.

Intergranular voids of grainstones also are filled with a sparry calcite mosaic and internal sediment; and the internal sediment which commonly overlies fringing sparry calcite is continuous around solution cavities and grains in such limestones.

Fissures and irregular surfaces

Locally, lime mudstones and shelly wackestones have fissures and/or irregular upper surfaces along a disconformity. The details of a fissure developed on a *Tetradium*-bearing limestone are shown and described in Figure 7. Fissures are sharp-edged, V-shaped cracks, 10-30 cm deep, descending into the limestone. Irregular surfaces are undulating to sharp-edged disconformity surfaces 20-30 cm across and 5-10 cm deep. The fissures and irregular upper surfaces are not soft sediment features because they transgress fossils, and hence are developed in brittle limestone. They are not late stage tectonic features because they are filled with internal sediment, or soils, or sedimentary deposits of the overlying material.

Cryptocrystalline (and microcrystalline) calcite patches

Grainstones beneath some major disconformities are altered in patches to cryptocrystalline (and microcrystalline) calcite. The patches are closely scattered and vary in size from a millimetre to several centimetres. The patches of cryptocrystalline (and microcrystalline) calcite grade into relicts of grainstone fabric which, in turn, grade into unaltered grainstone. Cavities and fissures wholly filled with internal sediment are associated with the cryptocrystalline patches. Grainstones also may be cemented in patches by cryptocrystalline calcite instead of sparry calcite. The cryptocrystalline calcite may be in patches in an otherwise sparry calcite-cemented grainstone or may be the sole cement present. Locally, the cryptocrystalline cement is faintly laminated (see Fig. 10B).

Bleaching (bleached zones)

The lime mudstones and shelly lime wackestones are normally black to dark grey to medium grey, but proximal to some disconformities, involving tens of centimetres, roughly parallel to and underlying the disconformity surface, limestone is bleached to a lighter grey, or to a cream tone, or to brown. XRD of black to dark-grey limestones shows pyrite as the colouring mineral. In bleached limestones, Fe-oxides may be the colouring mineral, or there is no colouring mineral. In the Glenrae Limestone Member, the formerly dark to medium grey limestones have been

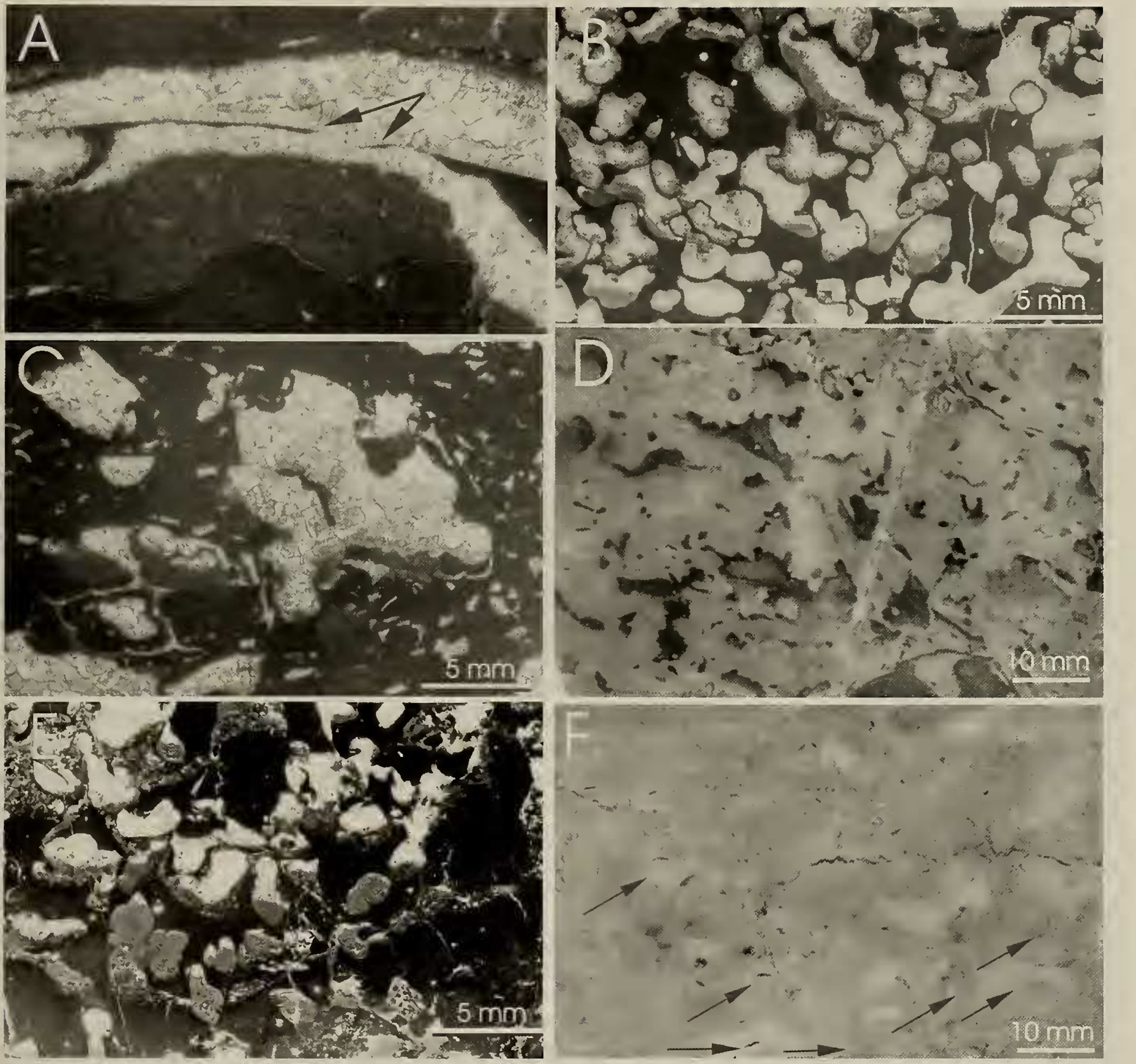


Figure 6. Thin sections and polished slabs of a variety of limestones produced by subaerial diagenesis. A. Enlarged fossil mold (Eodinobolus) leading to vuggy limestone; the floor of the enlarged cavity is shown in white dashed line; diagenetic sediment is in the lower part of the cavity; the micrite envelope around the Eodinobolus, and the fragmenting micrite envelope are arrowed. B. Inter-connected vughs of solution-enlarged Tetradium molds, here partially filled with diagenetic sediment, leading to development of vugular limestone (SUP 29176). C. Solution-enlarged Tetradium molds. D. Solution enlarged Tetradium molds partly filled with crystal silt leading to development of "Stromatactis" structures (note that the limestone is bleached to light grey); USGD 466143. E. Solution enlarged Tetradium molds with molds in the upper part of the view filled dominantly by sparry calcite and the lower part filled dominantly by crystal silt, the latter leading to the development of mottled limestone. F. Polished slab of mottled limestone wherein fossil molds are filled with crystal silt (some are arrowed where the upper part of the cavity has some sparry calcite lining the roof; note that the limestone is bleached to light grey.

bleached and, additionally, have been impregnated by light-toned calcrete as a cementing agent that renders them light grey. In the dark grey limestones of the Bourimbla, Manooka, and Gerybong Limestone Members, Fe content is 2-4%. In the light grey limestones of the Glenrae Limestone Member, Fe content is 0%-0.06%. Elemental maps (derived by SEM-EDS) of Fe concentration in the dark grey

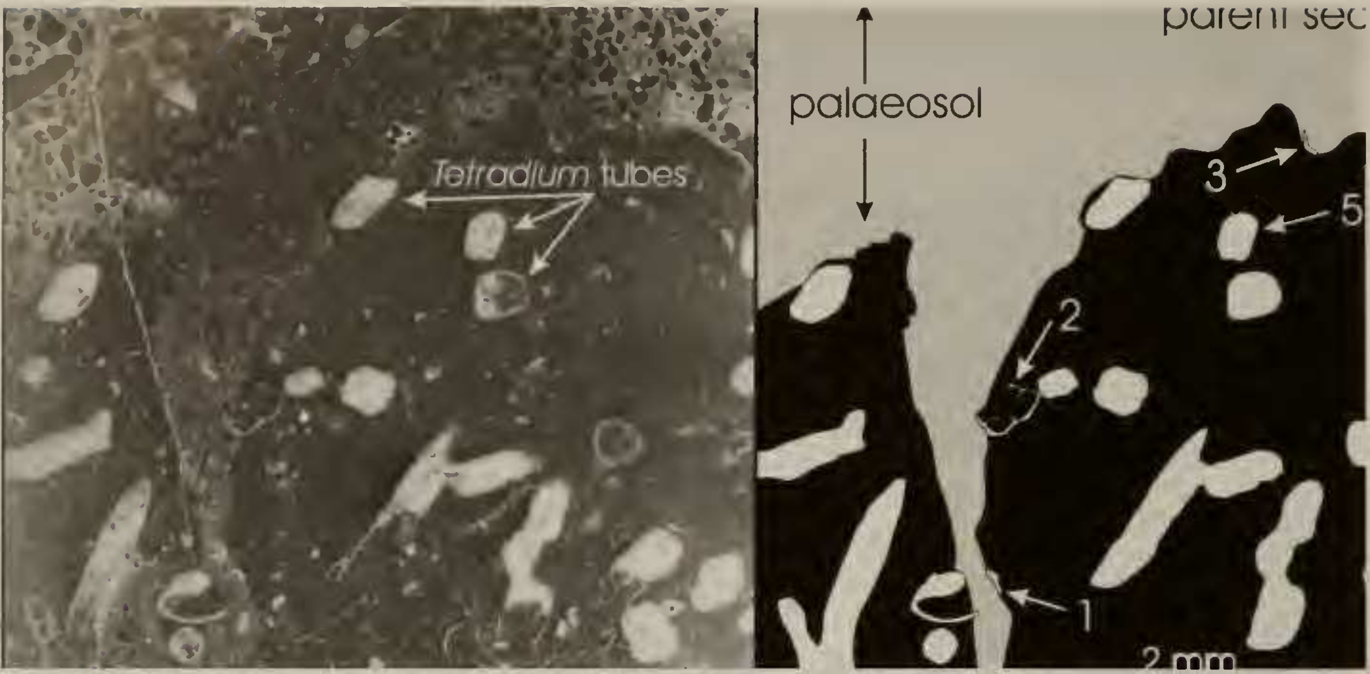


Figure 7. Thin section of a palaeosol infiltrating a downward narrowing fissure in Tetradium-bearing skeletal wackestone (USGD 46662). The paleosol is lithoclastic grainstone. The fissure truncates fossils in the underlying limestone. Some key features are arrowed: (1) outlier of a gastropod that has been truncated by the fissure; (2) Tetradium tubule truncated by the wall of the fissure; (3) inner wall of Tetradium tubule forming surface of the contact between palaeosol and underlying limestone – the interior of the Tetradium has been removed by erosion and/or solution; (4) shell of ostracod forming resistant surface to the contact between palaeosol and underlying limestone; (5) Tetradium as spar-filled mold (casts) or sediment filled corallites.

limestone compared to the light grey limestone, confirms that bleaching involved removal of Fe. The weathering surface on outcrops of the dark grey limestones provides a modern analogue for such bleaching in the Ordovician – the dark grey limestones at the modern weathering surface have a fine micro-laminated crust, 10-25 µm thick, of light grey calcium carbonate, where the Fe-bearing dark grey limestone has been altered (oxidised) and leached free of Fe. The bleaching of the modern weathered limestone surfaces is only an analogue in terms of Fe removal and change in tone from dark grey to light grey, because the crust on the weathered limestone is micro-laminated similar to a patina (cf. Clifford 2008), and not massive and mottled as the bleached limestones of Ordovician age.

LITHOLOGIES

The lithologies associated with subaerial disconformities are vugular limestone, mottled limestone, massive light grey limestone, lithoclast grainstone, calcrete-ooid grainstone, calcrete-ooid packstone and wackestone, palaeosols, and (terrigenous) mudstone.

Vugular limestone

Vugular limestone is usually a muddy limestone, such as skeletal wackestone, skeletal packstone, or lime mudstone, in which there are fossil-shaped to irregular vughs filled with sparry calcite or with internal sediment and sparry calcite (Fig. 8). The vughs are scattered to closely arrayed in the limestone, depending on the extent that the original limestone was fossiliferous. In geometry, the vughs also are clearly related to fossil content, where they are dissolved *Tetradium*, *Eodinobolus*, and *Alleynodictyon*, and in this context they are strictly fossil molds, but with solutional enlargement, the vughs grade in shape to irregular cavities. Small-scale conduits (filled with sparry calcite, or with internal sediment and sparry calcite) connect many of the vughs. The vugular limestone forms zones 10-100 cm thick under subaerial disconformities, and in this stratigraphic setting, the extent of infill by internal sediment decreases downwards from the subaerial disconformity surface. With increasing irregularity of the upper vugh shape, and with increasing vugh-fills of internal sediment partly filling the cavity to create a flat base to the vugh, vugular limestone becomes '*Stromatactis*' limestone (Fig. 6D; Semeniuk 1971). Note that this origin of '*Stromatactis*', that in the Daylesford Limestone is clearly derived by leaching

Figure 8. Outcrop of vugular limestone developed within Eodinobolus limestone. The arrows show sparry calcite filled fossil mold (1), diagenetic sediment-filled fossil mold (2), irregular sparry-calcite-filled vughs (3), vughs that are partially filled with diagenetic sediment with upper part filled with sparry calcite (4), and vughs that are nearly wholly filled with diagenetic sediment (5), the bases of which are outlined. Note that the limestone is bleached to light grey. Aligned calcite-filled tectonic fractures clearly are later features that postdate the vugular structures.

of *Tetradium* tubules, differs from the origin of '*Stromatactis*' proposed by Lees (1961) for the Waulsortian Mounds and its origins as proposed by Bathurst (1982) and Krause et al. (2004). With increasing irregularity of vugh shape, and with increasing vugh fills of internal sediment, vugular limestone grades into mottled limestone. The different fabrics, structures and lithologies produced by various pathways of solution and internal sedimentation are summarised in Figure 9. The contact with underlying sediment is sharp, and varies from highly irregular at the small-scale to planar.

Mottled limestone

Mottled limestone is developed in muddy limestones, such as skeletal wackestone, skeletal packstone, or lime mudstone (Fig. 6F). It is the end product of a process where vugular limestones with irregular and interconnecting cavities have been infiltrated by internal sediment. Within the mottled limestone, internal-sediment-filled irregular vughs dominate, but locally there are internal-sediment-filled enlarged fossil molds and some internal-sediment-filled fossil casts. As a rock type, mottled limestone is subordinate to vugular limestone. As with the vugular limestone, the mottles in this limestone, founded on cavities now filled with internal sediment, are scattered to closely arrayed, depending on the extent that the original limestone was fossiliferous. Small-scale conduits (filled with internal sediment) connect many of the mottles. The mottled limestone forms patches and local zones < 50 cm thick under subaerial disconformities. The contact with underlying sediment is sharp, and varies from highly irregular at the small scale to planar.

Massive light grey limestone

Massive light grey limestone is a complex of lithologies. As a broad overview, essentially there is patchy cementation by, and alteration of grainstone to cryptocrystalline calcite. The patches grade into relicts of the original texture, and they vary in size from a fraction of a millimetre to several centimetres, and are closely spaced to scattered in distribution. Where the patches are scattered, the altered limestone is mottled, consisting of grainstone areas which are interspersed with, and grade into, cryptocrystalline areas; where the patches are closely spaced, the limestone is fine-grained and dense with minor grainstone areas. Fossil molds, irregular solution cavities and fractures filled

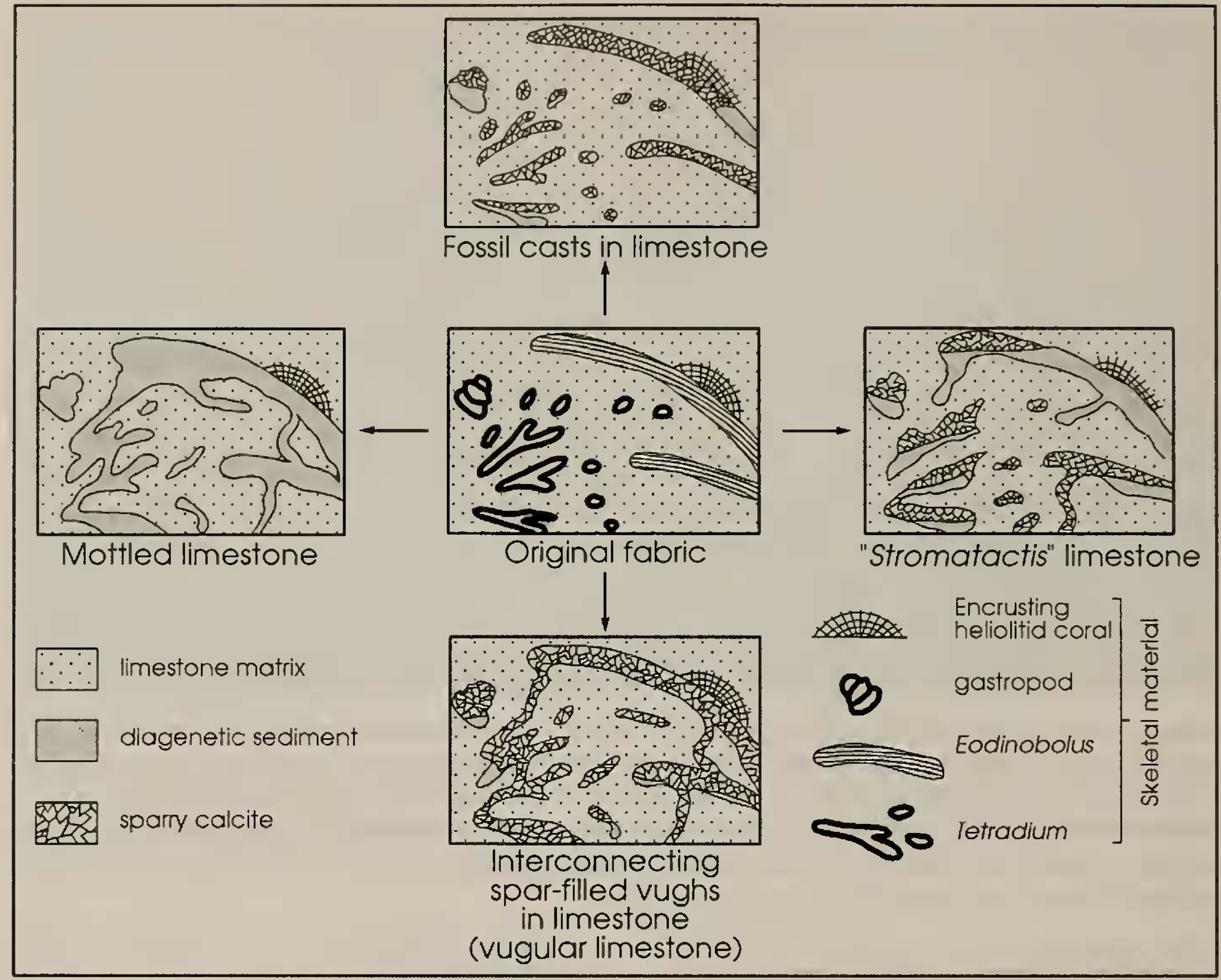


Figure 9. Pathways to develop lithologies and structures by solution, cavity enlargement, and diagenetic sediment infiltration: fossil molds in limestone, vugular limestone, "Stromatactis" limestone, and mottled limestone.

with crystal silt and pellets are associated with the cryptocrystalline calcite.

In detail, there are four lithotypes in the suite of mottled light grey limestone, and they grade in series from grainstone to mottled light grey limestone. At one extreme of the gradational series, the first lithology is a rock type that while it can be broadly described as a grainstone, is cemented interstitially by sparry calcite and by fine-grained (microcrystalline) calcite. Skeletal and lithoclastic grains in this grainstone are still evident. This limestone grades into the second type of grainstone that has increasing content of fine-grained (microcrystalline) calcite as interstitial cement, and the grains comprising the grainstone are more commonly altered to fine-grained (microcrystalline) calcite. As such, in this second type of grainstone, the distinction between fine-grained (microcrystalline) grains and fine-grained (microcrystalline) interstitial cement calcite is becoming blurred. The grainstone is being transformed to diagenetic 'muddy' limestone. The third limestone lithology is a massive fine-grained (microcrystalline) limestone wherein there are only vestiges of grains that once comprised the grainstone fabric, and the lithology is dominated by the fine-grained 'matrix', that is, it has become a diagenetic 'muddy' limestone. This lithology also has cracks and fissures ~ 1-2 mm in width, filled with fine-grained calcite and internal sediment, and grades into breccioid structure. This rock therefore has, with the patches of fine-grained calcite and the sediment-filled cracks and fissures, a light grey mottled appearance. The next stage of lithology development is a massive fine-grained light grey limestone with abundant cracks and fissures (filled with fine-grained calcite and with internal sediment) that impart a breccioid structure to the limestone. This final lithology in the gradational series also has a light grey mottled and locally brecciated appearance.

Lithoclast grainstone

Lithoclast grainstone is composed of medium to coarse-grained sand-sized lithoclasts, lithoclasts with altered periphery, and lesser remanié fossils, calcrete ooids, and fossils, as well as some gravel-sized lithoclasts and remanié fossils. The lithoclast grainstones are structureless to laminated, with gravel-sized components aligned to lamination, or defining the lamination. The grainstones are cemented by sparry calcite.

Calcrete-ooid grainstone

Calcrete-ooid grainstone is brown and composed of medium to coarse-grained sand-sized calcrete ooids and lesser remanié fossils, and also some gravel-sized lithoclasts and remanié fossils. The calcrete ooid grainstones are structureless. The grainstones are cemented by sparry calcite. Interstitial to the grains there is some minor internal sediment.

Calcrete-ooid packstone and wackestone

Calcrete-ooid packstone and wackestone are brown to grey and composed of medium sand-sized calcrete ooids and lesser remanié fossils, and also some gravel-sized lithoclasts and remanié fossils set in a matrix of lime mudstone with scattered sand-sized fossil skeleton fragments. The calcrete ooid packstone and wackestone are structureless to burrowed. Calcrete-ooid packstone and wackestone grade into palaeosols.

Palaeosols

Palaeosols are structureless to mottled, brown to grey, grain-supported and composed of medium to coarse, sand- and gravel-sized, round to irregular, lithoclasts, calcrete-coated lithoclasts (mainly calcrete ooids, and minor pisolites with thin calcrete envelopes), peripherally altered lithoclasts, calcrete-coated remanié fossils, and silicified remanié fossils (Figs 7 and 10). Crystal silt occurs in patches and either completely fills, geopetally rests on grains, or floors intergranular voids (Fig. 10). Locally, laminar calcrete is developed in patches (Fig. 10B). Palaeosols in the Daylesford Limestone have been cemented by cryptocrystalline calcite and, in patches, by sparry calcite. Lithologically, the sediments resemble modern and Pleistocene soils developed on carbonate sediments (Read 1974).

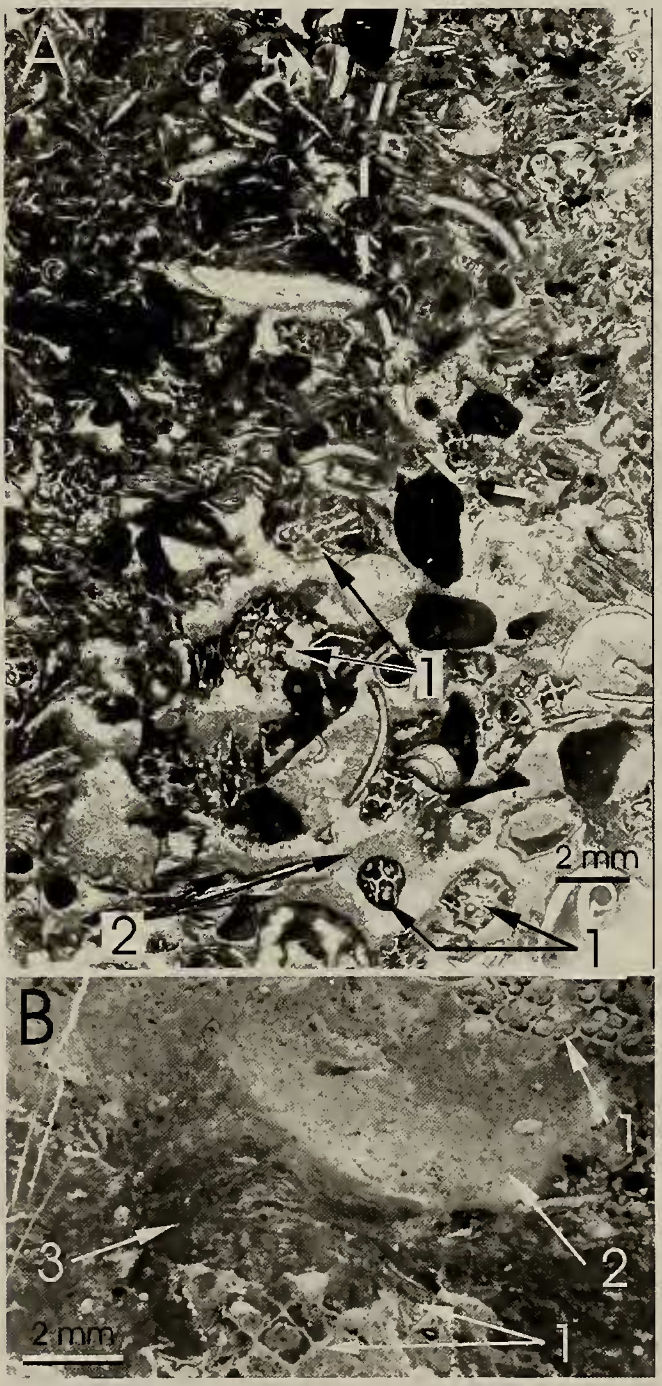


Figure 10 RIGHT. Thin section of palaeosols developed on Tetradium-bearing limestone. A. Palaeosols on Tetradium-bearing skeletal wackestone (SUP 29172). The arrows show fragments of Tetradium with mud within the tubules, and crystal silt that has infiltrated the intergranular void network resting geopetally on tops of grains. The upper right side of the photograph is an open framework of grains (lithoclasts and remanié fossils of Tetradium) and voids with infiltrated crystal silt, separated by the dashed line from the upper left side of the photograph which is an framework of grains (lithoclasts and remanié fossils of Tetradium) and voids packed with infiltrated crystal silt. B. Complex palaeosol fabric composed of (1) remanié fossils of Tetradium partly filled with marine sediment and partly filled with diagenetic sediment, (2) vughs filled with diagenetic sediment, and (3) patches of laminar calcrete encrusting the remanié fossil.

The palaeosols form thin horizons (generally up to 10 cm thick). The contact with underlying parent sediment is highly irregular and locally gradational; the soil commonly infiltrates along cracks and fissures (Fig. 7) which penetrate underlying limestone up to 30 cm, or forms a layer on an irregular disconformity surface. Contacts with overlying marine limestone commonly are mixed by burrows.

Palaeosols are developed mainly on muddy limestones in the Daylesford Limestone. Palaeosols are more difficult to recognise in grainstone sequences because of their lithologic similarity to lithoclastic grainstones in the Formation, and because they are more likely to have been reworked under high energy conditions into the marine grainstones overlying the disconformity (and hence cease being palaeosols). Generally, palaeosols are distinguished from lithoclast grainstone, and calcrete-ooid grainstone in that the former are in situ on the disconformity, whereas the latter have been transported and show transportation structures, and current depositional structures (e.g., aligned platy fossils).

(Terrigenous) mudstone

Mudstone comprising terrigenous clay and quartz silt is a brown, structureless fine –grained rock. Generally, it is fossil-free (but see later). This mudstone is interpreted as a palaeosol developed by solution of a marl, or a lime wackestone/mudstone that had a small component of clay mineral, mica, and quartz silt.

Silicified limestone

The lithologies of vugular limestone, and fossiliferous limestone such as skeletal wackestone and skeletal packstone with solution cavities and sparry calcite filled fossil casts, can be silicified. The silica, as noted above, replaces both fossils and sparry calcite. The horizons of silicification coincide with leaching beneath some subaerial disconformities, as evident in the Bourimbla Limestone Member, between Bourimbla and Manooka Limestone Members, within the Manooka Limestone Member, and between Daylesford and Quondong Limestones. Sparry calcite fringing solution cavities in these horizons is silicified whereas later generations are not. Silicified fossils occur as clasts in lithoclast grainstones overlying some disconformities.

STRATIGRAPHIC PROFILES ASSOCIATED WITH DISCONFORMITIES

Subaerial disconformities are located in a number of stratigraphic levels in the Daylesford Limestone (Figure 11). They are underlain by and associated with a diagenetic stratigraphic sequence and sedimentary stratigraphic sequence consisting of, in descending order:

4. the new cycle of sediments overlying the disconformity;
3. grainstone composed of lithoclasts, remanié fossils and calcrete-coated grains, or a palaeosol, both several centimetres thick;
2. altered host rock (tens of centimetres to tens of metres thick); and
1. unaltered host rock.

The most important factor to vary the profile is the type of host rock (Fig. 12), i.e. grainstone versus muddy limestone. Profiles developed on the two end-member host sediments differ in detail. For instance, palaeosols are mostly developed on muddy limestone, and leaching is the most common phenomenon in the altered muddy limestone, whereas for grainstones, palaeosols are generally absent, and cryptocrystalline (and microcrystalline) calcite (calcrete) patches are the most important features.

There is a gradient of diagenetic effects and lithology from the disconformity downwards (Fig. 13). Thus irregular cavities, enlarged fossil molds and internal sediments are most common in the upper parts of a diagenetically subaerially altered profile, with diagenesis decreasing downwards from the disconformity, and lower parts of the diagenetically altered profile mainly containing spar-filled fossil molds, enlarged fossil molds, and only minor internal sediment.

Ten types of diagenetically altered profiles are recognised under subaerial disconformities in the Daylesford Limestone:

1. erosionally truncated vugular limestone with coralline encrustation on the disconformity;
2. erosionally truncated vugular limestone without palaeosol cover;
3. erosionally truncated vugular limestone with thin palaeosol cover;
4. muddy limestone with thin palaeosol cover with calcrete ooids and remanié fossils;
5. muddy limestone with thick palaeosol cover with calcrete ooids and remanié fossils;
6. muddy limestone with lithoclastic and calcrete ooid grainstone and remanié fossils;
7. solution-altered grainstone with overlying lithoclastic and calcrete ooid grainstone;
8. thick calcrete developed on grainstone (= Glenrae Limestone Member);

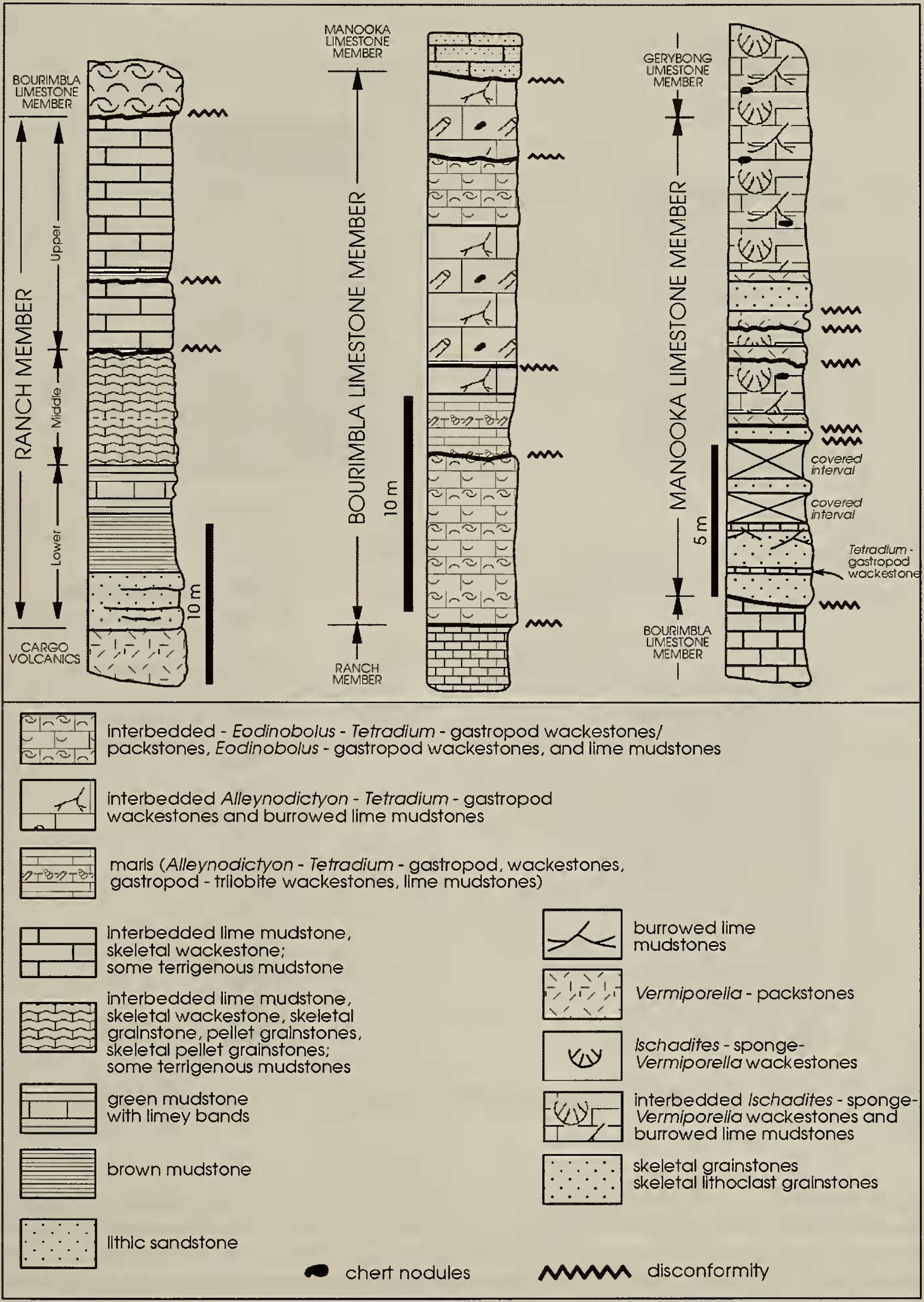


Figure 11. Stratigraphic columns of the Ranch Member, and Bourimbla and Manooka Limestone Members showing sequences of lithologies and occurrence of disconformities.

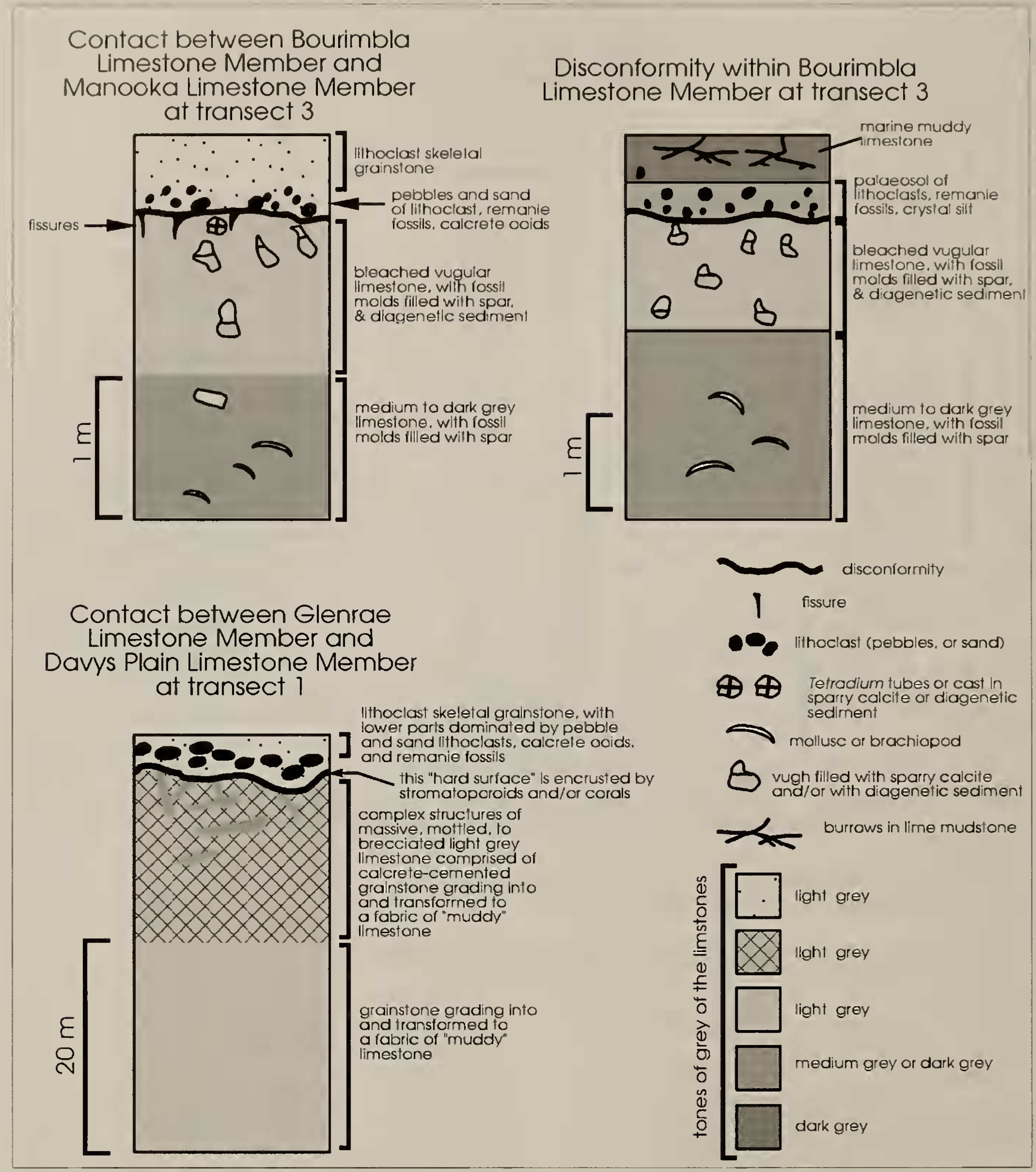


Figure 12. Some representative stratigraphic profiles across disconformities in the Daylesford Limestone.

Figure 13 RIGHT. A. Stratigraphic profiles west to east across the Bowan Park area of the Bourimbla Limestone Member showing correlation of disconformities and the occurrence of paleosols and vugular and mottled limestones associated with subaerial exposure. B. Details of subaerial diagenesis showing stratigraphic distribution of sparry calcite, diagenetic sediment, pellets and lithoclasts, mottled limestone and "Stromatactis" limestone beneath disconformities (modified from Semeniuk 1971). Stratigraphic location of outcrops, slabs and thin sections illustrated in earlier Figures are shown on the profile.

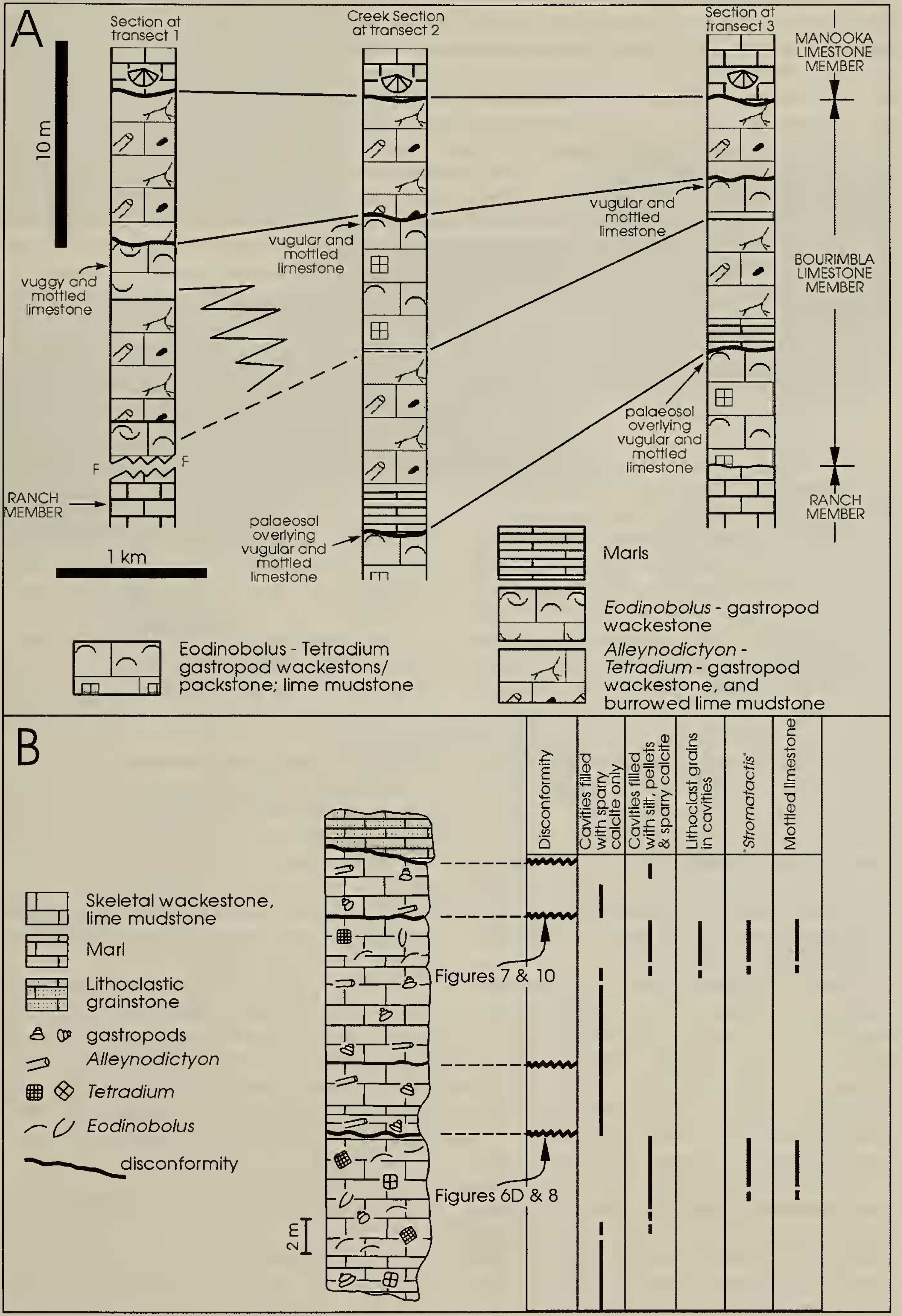

A
Section at transect 1
Creek Section at transect 2
Section at transect 3
10 m
1 km
MANOOKA LIMESTONE MEMBER
BOURIMBLA LIMESTONE MEMBER
RANCH MEMBER
RANCH MEMBER
vuggy and mottled limestone
vugular and mottled limestone
vugular and mottled limestone
palaeosol overlying vugular and mottled limestone
palaeosol overlying vugular and mottled limestone
F
F
Marls
Eodinobolus - gastropod wackestone
Alleynodictyon - Tetradium - gastropod wackestone, and burrowed lime mudstone
Eodinobolus - Tetradium gastropod wackestons/ packstone; lime mudstone
B
Skeletal wackestone, lime mudstone
Marl
Lithoclastic grainstone
gastropods
Alleynodictyon
Tetradium
Eodinobolus
disconformity
2 m
Figures 7 & 10
Figures 6D & 8
Disconformity
Cavities filled with sparry calcite only
Cavities filled with silt, pellets & sparry calcite
Lithoclast grains in cavities
"Stromatactis"
Mottled limestone

Figure 14 RIGHT. Stratigraphic profiles showing the weathering (calcretised) transition from sandy facies of the Oakley Limestone Member to the east to the muddy facies of the Gerybong Limestone Member to the west. The Glenrae Limestone Member is mottled with grainstone at the top of the Oakley Limestone Member. Photographs show the nature of the bleached light grey limestone that comprises the Glenrae Limestone Member. A. Polished slab showing light grey (bleached) limestone; evident here are the mottles throughout the limestone, and its brecciated nature along the lower margin of the polished slab. B. Thin section of grainstone of the upper Oakley Limestone Member impregnated interstitially with fine grained calcite (calcrete). C. Thin section of former grainstone of the Glenrae Limestone Member (USGD 41806) impregnated interstitially with fine grained calcite (calcrete) and skeletal molds filled with crystal silt (arrowed). D. Thin section of former grainstone of the Glenrae Limestone Member (USGD 41806) impregnated interstitially with fine grained calcite (calcrete) [medium grey lithology] and sharp-edged fissures (marked by arrows) filled with diagenetic sediment of (mainly) crystal silt and pellets [light grey lithology]; the sharp edges to the fissures, and multiplicity of fissures will create a brecciated appearance (see A above).

9. wackestone/lime-mudstone (marl) with overlying sheet of (terrigenous) mudstone;
10. silicified limestone.

The stratigraphy of some of these profiles is shown in Figures 12 and 13. The profile varies in thickness from 30 cm (beneath minor disconformities) to a maximum of 45 m beneath the major disconformities at the base of the Davys Plains Limestone member. The distribution of lithologies in the massive light grey limestone suite is shown in Figure 14. There is also lithologic variation of diagenetic products developed along an unconformity and, axiomatically, in profile. Fossil content, type of primary skeletons, granulometry, and Ordovician local topography, for example, can affect the extent or intensity of diagenesis and the pathway it may have taken.

The critical features of the profiles are the palaeosols, the irregular surfaces with infiltrated palaeosols, the vugular limestones under the disconformities, the mottled limestones also under the disconformities, the restriction of internal sediment under disconformities, and the grain types associated with subaerial disconformities, namely, the lithoclasts, calcrete ooids and remanié fossils.

At many stratigraphic levels in the Daylesford Limestone, the subaerially altered limestones have been reworked or stripped with the disconformity surfaces cut into altered limestone: internal sediment and infiltrated soils occur in solution cavities and fissures in altered limestone beneath some disconformities and/or soil particles have been reworked into marine sediments overlying disconformities. Reworked palaeosols are evident where lithoclastic skeletal grainstone rests with sharp contact on altered limestone. In addition to containing normal marine fossils, these grainstones contain gravel-sized lithoclasts, calcrete-coated lithoclasts, peripherally-altered lithoclasts and remanié fossils. *Girvanella*, coral or stromatoporoid encrustations occur on some gravel-sized lithoclasts indicating that reworking occurred under high-energy conditions during a marine phase following the subaerial exposure. The lithoclastic grainstones above such disconformities are distinguished from palaeosols by their sedimentary structures and marine fauna. Palaeosols, in contrast, contain only minor unaltered marine fossils, are poorly bedded, and commonly gradationally overlie and infiltrate the parent sediment.

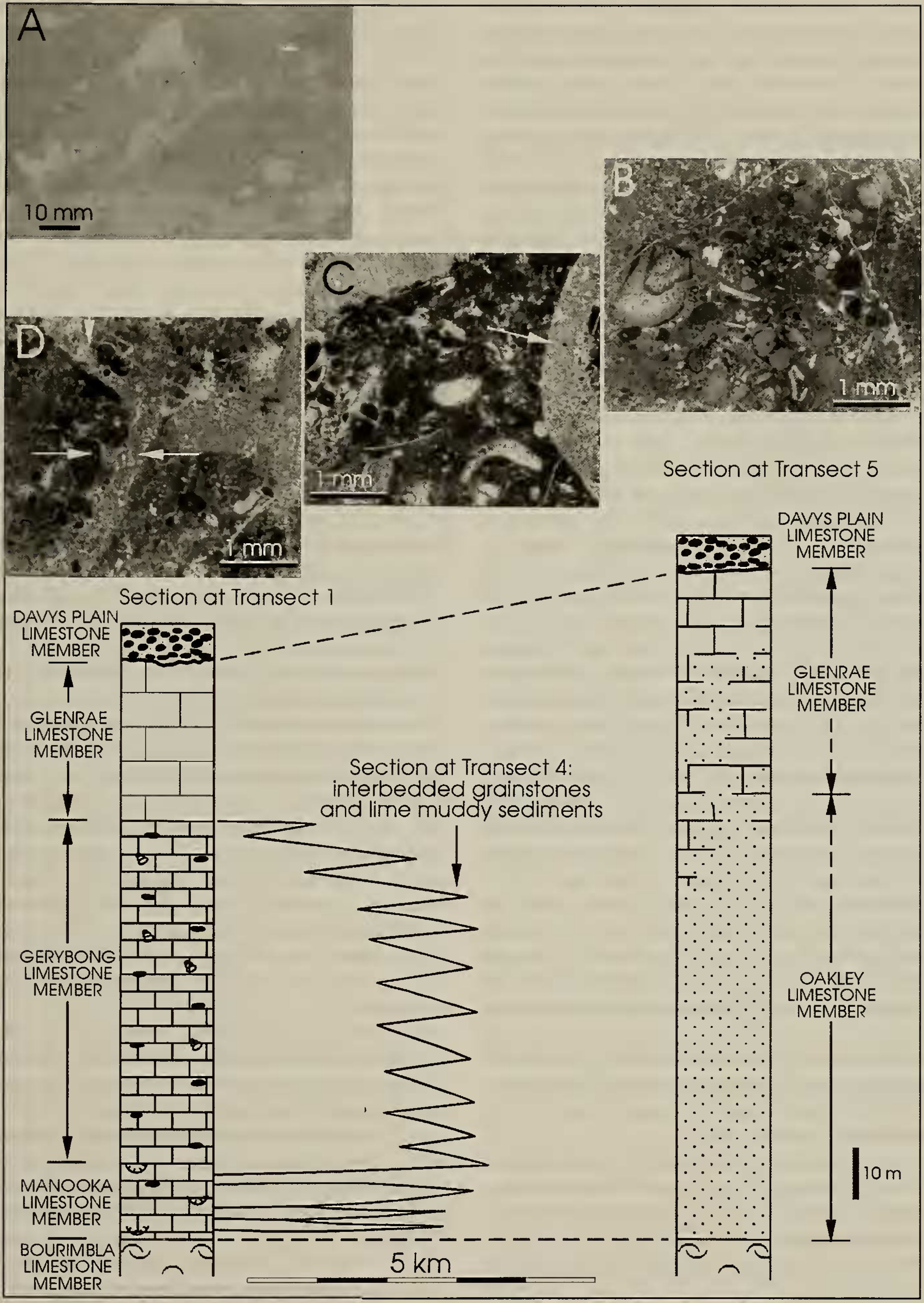
Thus, weathering, erosion, and subsequent marine reworking of a profile down into the altered limestone zone resulted in lithoclastic grainstones that contain soil particles and gravel-sized clasts of altered limestone, including cemented limestone, leached limestone, remanié fossils, and silicified fossils.

Biogenically reworked palaeosols also occur where (marine) muddy sediments overlie a disconformity. The zone of reworking is thin and consist of burrow-mottled, lithoclastic skeletal wackestone or packstone, which may grade down into undisturbed palaeosols and grade up into marine limestone lacking exotic grains. In this case, burrowing organisms mixed soil and muddy marine sediment.

In terms of silicified limestones, there is an abundance of silicified fossils and silicified sparry calcite mosaics in altered muddy limestone beneath disconformities in the Daylesford Limestone. In these leached horizons, silica replaced fossils that resisted solution and early sparry calcite that fringed molds, thereby preserving the fossil outlines.

DISCUSSION AND CONCLUSIONS

This Discussion is structured into an interpretative section on the grains, fabrics and structure, and lithologies developed by subaerial exposure of the


A
10 mm
B
1 mm
C
1 mm
D
1 mm
Section at Transect 5
DAVYS PLAIN LIMESTONE MEMBER
GLENRAE LIMESTONE MEMBER
OAKLEY LIMESTONE MEMBER
10 m
Section at Transect 1
DAVYS PLAIN LIMESTONE MEMBER
GLENRAE LIMESTONE MEMBER
Section at Transect 4: interbedded grainstones and lime muddy sediments
GERYBONG LIMESTONE MEMBER
MANOOKA LIMESTONE MEMBER
BOURIMBLA LIMESTONE MEMBER
5 km

Ordovician limestones, including the occurrence of calcrete, the occurrence of calcrete without plants, the significance of bleaching, the significance of the Glenrae Limestone Member, the occurrence of silica, and the environmental implications of diagenesis and pedogenesis in relation to landscape setting, palaeohydrology and depth of the vadose zone, climate, and hydrochemistry that can be inferred from the subaerial diagenesis and pedogenesis of these limestones.

In the first instance, the altered limestones beneath disconformities in the Daylesford Limestone are classic expressions of subaerially altered profiles. Within the sequence there are numerous indicators of the early nature of this subaerial diagenesis. Alteration of carbonate sediments and limestone in modern subaerial environments (Friedman 1964; Matthews 1968; Purdy 1968; Esteban and Klappa 1983) and inferred ancient subaerial environments (Schlanger 1963; Dunham 1969a), indicate that there are four main processes operating in modern environments: 1. solution; 2. cementation by sparry, cryptocrystalline and microcrystalline calcite; 3. internal (diagenetic) sedimentation and illuviation; and 4. recrystallisation of limestone to cryptocrystalline (and microcrystalline) calcite to form calcrete. For the Daylesford Limestone, the occurrence of vugular limestones and mottled limestones immediately beneath disconformities indicates the close association between dissolution and disconformity surfaces, and subaerial exposure (Semeniuk 1971). Lack of appreciable structural and fabric alteration lower in the stratigraphic profile (the unaltered host rock), is similar to phreatic or deep levels of the vadose zones in modern weathering profiles where micro-solution and replacement (of metastable aragonite and high-Mg calcite), and cementation by sparry calcite, are the main diagenetic processes, but the structure, fabric, and texture of the sediment remain unaltered (Friedman 1964; Land 1967; Matthews 1967). In terms of calcite precipitation and cementation, calcite mosaics in the Daylesford Limestone in solution cavities of all lithologies and in intergranular voids of grainstones are analogues of those precipitated in fresh-water diagenetic environments (Friedman 1964; Land 1967; Matthews 1967).

In the context of the amount of dissolution of calcium carbonate effected on the limestones during Ordovician subaerial exposure, rock types such as marls would generate insoluble residues and form terrigenous mudstones as palaeosols. In a situation where a marine transgression immediately followed, these originally terrigenous muddy substrates may be colonised by marine biota, or by burrowing organisms, that resulted in mixing of the mudstones into the overlying sediments.

Calcrete ooids, lithoclasts, peripherally-altered grains and remanié fossils are common in modern and Pleistocene calcareous soils (Brown and Woods 1974; Read 1974). The modern soils form in situ by alteration of unconsolidated sediments, or by disintegration and alteration of partly lithified to lithified rock. Palaeosols developed on muddy limestones of the Daylesford Limestone were probably originated by surficial break-up of the sediment into sand- and gravel-sized mudstone clasts and component fossils, controlled by peds and cracking, as suggested by fissures in the underlying limestone and the locally gradational contact of soil with parent sediment. These surface grains were subsequently peripherally altered and calcrete-coated, i.e., they formed the nuclei for the calcrete-ooids. The break-up of fossiliferous and pellet-bearing lime mudstone, and the release of fine-grained mudstone clumps (or clots), pellets and shells provided some of the source material that would infiltrate the solution cavities developing in the muddy limestone. In contrast, palaeosols developed on grainstones formed on an already sandy parent, and peripheral alteration and calcrete-coating of grains, cementation, and diagenetic (internal) sedimentation would have been the main surface alteration processes.

In sediments above the disconformity, sand- and pebble-sized lithoclasts of skeletal limestone with sparry calcite-filled and diagenetic sediment-filled fossil molds truncated along the grain boundary, and clasts of vugular limestone indicate that the disconformity-related solution features were eroded and reworked into the next cycle of sedimentation. Lithoclasts of sparry calcite-cemented grainstone also indicate early cementation. Sparry calcite lining solution cavities and cementing grainstones indicate penecontemporaneous subaerial solution and cementation.

Internal (diagenetic) sedimentation and illuviation are important processes in modern subaerial environments, with fine-grained material being transported gravitationally though the vadose zone. These processes and sedimentary products signal subaerial conditions both in the generation of specific vadose-environment grain types, and in the vadose conditions of delivery. Internal sediments (diagenetic sediments) and illuvium can develop specific rock types under subaerial disconformities. As fine-grained material, they fill pore spaces, solution cavities, and other types of opening such as fissures and ped boundaries. Taken to completion, diagenetic sedimentation and illuviation can finally plug all porosity in the upper parts of the host material. In the case of the Daylesford Limestone, diagenetic sedimentation and illuviation resulted in partially filled vughs (some of which are termed '*Stromatactis*' limestone), partially filled inter-granular pores of grainstones, and fully plugged cavities that comprise the mottled limestones. In a study of the Townsend Mound in New Mexico, for example, Dunham (1969a) related diagenetic sediment in cavities and inter-granular pores to remobilised crystal silt in the vadose zone, gravitationally descending but screened by the small pore spaces and fine-scale fractures in a subaerially exposed limestone, thus accounting for the well sorted nature of much of this type of internal sediment. However, there are other types of internal sediment and illuvium that were: 1. produced internally in the rock by the disintegration of polymineralic and/or multi-textured skeletal grains, 2. produced as insoluble residue at the surface of the rock and washed in as illuvium, and 3. delivered as aeolian carbonate dust to the rock surface and washed in as illuvium. Pellets within the suite of diagenetic sediment in the Daylesford Limestone may be fine-grained calcreted grains washed into the profile by vadose waters, or algal or calcrete micrite envelopes that have fragmented, after the primary calcareous interior of a calcareous skeleton, to which they were envelopes, has dissolved. Lithoclasts that occur within the internal sediment suite, if derived from the surface, clearly have been fine enough grains to infiltrate the pores, solution cavities, fractures and fissures of the subaerially exposed limestone, but some sand-sized 'lithoclasts' have been formed by collapse of a limestone matrix into its enlargening solution cavity (essential an in situ 'auto-microbreccia'). All five types of diagenetic (internal) sediment and illuvium indicate gravitational delivery and hence vadose conditions.

Calcrete is an important part of the subaerial diagenesis of the Daylesford Limestone. While occurring as calcrete-ooids, mottled calcrete, and as massive calcrete, its most prevalent form is expressed as recrystallisation of limestone to cryptocrystalline (and microcrystalline) calcite. Cementation of grainstone by cryptocrystalline calcite (calcrete), and recrystallisation of grains to cryptocrystalline calcite (calcrete) is best developed beneath major subaerial disconformities and is commonly associated with solution and internal sediments.

Fine-grained calcite, where it is a replacement of (former) grainstones, and the cementation of grainstones by fine-grained calcite are analogues of Quaternary calcretes (Gile et al. 1966; Read 1974; Semeniuk and Meagher 1981). In modern environments, solution and then rapid precipitation of carbonate by vadose waters produce patches of cryptocrystalline calcite which either replaces grains or occurs as cement. These patches progressively enlarge, locally forming massive, fine-grained limestone, but more generally forming mottled limestone (Read 1974; Semeniuk and Meagher 1981). In the Daylesford Limestone, thick, porous grainstones allow widespread and deep percolation by vadose waters and, consequently, the calcrete alteration in grainstones is pervasive in upper parts of the profile, and developed to some depth. In contrast, low porosity in muddy limestones allow vadose waters access only through cavities such as fossil molds, enlarged fossil molds, and other interconnecting vughs.

In this context, one of the major disconformities, where sedimentation style changed from that dominated by low-energy muddy lime sediments (the Bourimbla, Manooka, and Gerybong limestone members) to one dominated by high-energy sandy and gravelly calcareous sediments, is the contact between suite of limestones of the Gerybong/Glenrae Limestone Member and the Davys Plains Limestone Member. This major subaerial disconformity and change in sedimentation style is marked by the development of massive calcrete. At this stratigraphic interval, western parts of the Daylesford Limestone, where muddy lime sediments dominated, the calcrete is relatively thin, though it does exhibit features of mottling, fine-grained calcite cementation, and bleaching. Eastern parts of the Daylesford Limestone, where sandy lime sediments dominated, the stratigraphic pile was thick, and porous lime sand subject to deep percolation by vadose waters, the calcrete is relatively thick, and calcrete development has gone to completion, with development of mottled calcrete, massive calcrete, and fissured and fractured limestone (brecciated) with calcrete and diagenetic sediment (mainly crystal silt) filling the fissures and fractures.

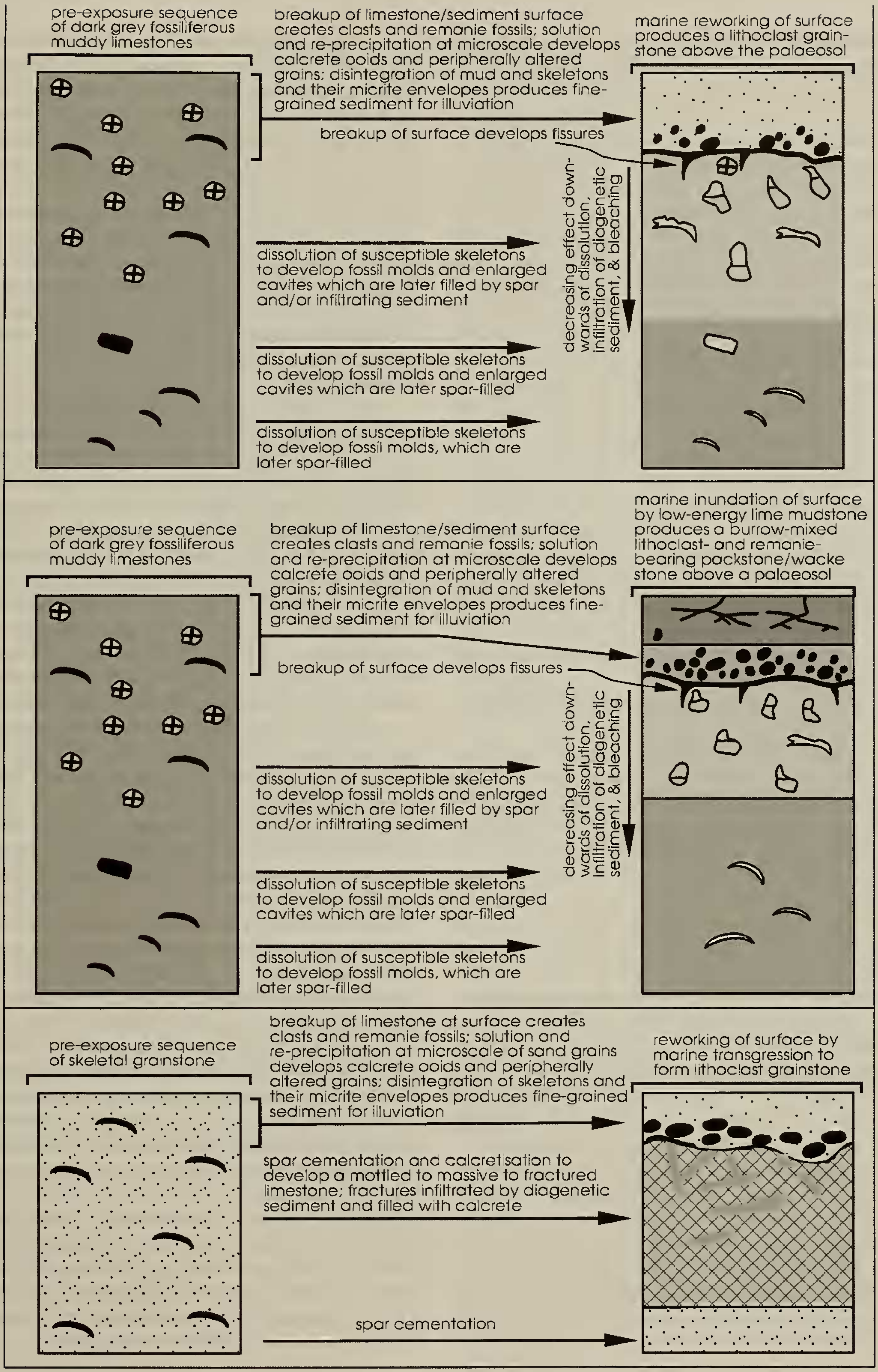
There is a notable lack of abundant calcrete pisolites (in palaeosols and reworked palaeosols) and absence of in situ laminar calcrete (at tops of grainstone sections altered to cryptocrystalline calcite). Both pisolitic and laminar calcrete are common in fully developed Quaternary calcrete profiles (Gile et al. 1966; Read 1974). Pisolites develop where calcrete envelopes nucleate on gravel grains or where calcrete accretion is thick. Laminar calcrete developed in Quaternary soil profiles is only a few centimetres thick (Gile et al. 1966; Read 1974). Erosion and stripping of Daylesford Limestone soils down to altered grainstones may have stripped laminar calcrete. There are clasts of laminar calcrete in the lithoclastic grainstones above disconformities, indicating that it had been present in the profile. However, it may not have been well developed. Gile et al. (1966) consider laminar calcrete to form only after lower horizons of a profile are plugged by cryptocrystalline calcite, with the laminar calcrete forming above the plugged zone where vadose water movement is impeded. Calcretisation of grainstones in the Daylesford Limestone may not have proceeded to the extent that lower parts of the profile were fully impregnated. The factor of time, or duration of exposure, may be reasons for this. On the other hand, continual erosional stripping of the area along the Molong Volcanic Belt, precluding mature calcrete development, may be another reason in that laminar calcrete is not common as an in situ layer. With continual erosional stripping, surface soils, and the immediately underlying laminar calcrete would be the first materials to be eroded. Figure 10B shows that laminar calcrete was present in the subaerially altered profiles. The lithoclast of veined laminar calcrete illustrated in Figure 3B also shows that laminar calcrete was present but it has been stripped and reworked.

There are various types of calcrete as described by Knox (1977), Klappa (1978), Semeniuk and Meagher (1981), and Wright and Tucker (1991). They can be summarised as belonging to two end-members of a spectrum of types: alpha calcretes - those generated dominantly by abiotic processes; beta calcrete - those with a biogenic or biologically mediated structure/fabric. Calcretes described by Gile et al. (1966) and some by Knox (1977) illustrate those that largely reflect abiotic processes. Microscale solution and re-precipitation in arid climates, where rainfall is seasonal and is followed by rapid evaporation, often results in abiotically formed microcrystalline or cryptocrystalline calcite mosaics (that are calcrete). Knox (1977), Klappa (1978), and Semeniuk and Meagher (1981) describe calcretes that have structure/fabric indicating biological mediation, with an abundance of permineralised, or calcrete coated filaments of fungi or of algae, and root hairs. Some of the calcretes described by Knox (1977) reflect combined abiotic and biotic processes. In many of the ancient and Quaternary calcrete, there is evidence of biomediation of calcrete development by the occurrence of fungi hyphae, algal threads, and plant root hairs (Knox 1977; Klappa 1978; Semeniuk and Meagher 1981; Wright and Tucker 1991). In this context, the calcretes in the Daylesford Limestone are alpha-types, lacking evidence of biomediation, and indicate that land plants were not instrumental in calcrete development. Rather, calcrete development was a product of solution and precipitation of metastable skeleton grains at microscale. Similarly, and corroboratively, there is an absence of plant root structures in the palaeosols, again indicating that land plants were not instrumental in palaeosol development.

Bleaching is an important product of subaerial diagenesis in these Ordovician limestones, and is a significant indicator of Ordovician subaerial exposure. Primary muddy limestones in the sequence are commonly dark grey to medium grey, as described above, with the dark colouration due to Fe-sulphides. Under disconformities, the limestones are bleached to light grey, very light grey, or even a cream tone. This, essentially, exhibits the oxidation and mobilisation of Fe-sulphides. This type of bleaching is common in modern subaerially exposed materials where the colouring agents such as Fe minerals, are mobilised away from the surface. For instance, the grey calcilutites of the Holocene coastal sequences of the Canning Coast in Western Australia are bleached to cream tones by exposure and oxidation of the Fe sulphides (Semeniuk 2008). The modern weathering surfaces of the Fe-bearing dark grey Ordovician limestones at Bowan Park have a thin crust or patina of Fe-free light grey carbonate, as described earlier. They provide modern analogues of how dark grey Fe-bearing limestone can be bleached under subaerial conditions to be bleached to a cream tone.

A summary in general form of the main processes operating during Ordovician subaerial exposure of the marine limestones, to produce three end-member stratigraphic profiles, is provided in Figure 15. Under subaerial conditions impermeable mudstones best produce palaeosols and fissures, irregular surfaces, and microkarst. Grainstones are indurated by sparry calcite but, because of their permeability, also best produce calcrete profiles wherein the fine-grained calcite (as calcrete) functions as an additional cementing agent. Once cemented, these indurated grainstones are subject to further calcretisation, but also to fracturing and development of fissures within which calcrete can precipitate and diagenetic sediment can

Figure 15 RIGHT. Processes operating during Ordovician subaerial diagenesis and pedogenesis to generate the various grain types, fabrics, structures, lithologies, and stratigraphic sequences diagnostic of subaerial exposure of lime grainstones and muddy limestones.


pre-exposure sequence of dark grey fossiliferous muddy limestones
breakup of limestone/sediment surface creates clasts and remanie fossils; solution and re-precipitation at microscale develops calcrete ooids and peripherally altered grains; disintegration of mud and skeletons and their micrite envelopes produces fine-grained sediment for illuviation
marine reworking of surface produces a lithoclast grainstone above the palaeosol
breakup of surface develops fissures
decreasing effect downwards of dissolution, infiltration of diagenetic sediment, & bleaching
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later filled by spar and/or infiltrating sediment
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later spar-filled
dissolution of susceptible skeletons to develop fossil molds, which are later spar-filled
pre-exposure sequence of dark grey fossiliferous muddy limestones
breakup of limestone/sediment surface creates clasts and remanie fossils; solution and re-precipitation at microscale develops calcrete ooids and peripherally altered grains; disintegration of mud and skeletons and their micrite envelopes produces fine-grained sediment for illuviation
marine inundation of surface by low-energy lime mudstone produces a burrow-mixed lithoclast- and remanie-bearing packstone/wacke stone above a palaeosol
breakup of surface develops fissures
decreasing effect downwards of dissolution, infiltration of diagenetic sediment, & bleaching
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later filled by spar and/or infiltrating sediment
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later spar-filled
dissolution of susceptible skeletons to develop fossil molds, which are later spar-filled
pre-exposure sequence of skeletal grainstone
breakup of limestone at surface creates clasts and remanie fossils; solution and re-precipitation at microscale of sand grains develops calcrete ooids and peripherally altered grains; disintegration of skeletons and their micrite envelopes produces fine-grained sediment for illuviation
reworking of surface by marine transgression to form lithoclast grainstone
spar cementation and calcretisation to develop a mottled to massive to fractured limestone; fractures infiltrated by diagenetic sediment and filled with calcrete
spar cementation

infiltrate. Subaerial exposure and dissolution of marls produces "terrigenous" mudstones as palaeosols, with terrigenous clay and quartz silt as insoluble residue. At smaller scales, there are several key processes operating: (1) muddy limestones disintegrate at the surface into components of clasts (probably controlled by ped structure), fossils, broken fossils, and into mud particles; (2) subaerially exposed sites develop calcrete ooids (the result of solution of metastable skeletons and clasts of disintegrated sediment, and its reprecipitation as thin envelopes of stable fine-grained calcite); and (3) pellets in palaeosols and in diagenetic sediment are disaggregated micrite envelopes following skeletal dissolution, and crystal silt may be mechanically derived by internally screened crystal fragments (following Dunham 1969a) but also may be relatively less soluble calcite particles derived from polymineralic and/or multi-textured shells differentially disaggregated under subaerial conditions. The suite of diagenetic and pedogenic products described in this paper, as illustrated in Figure 15, from grain-scale to fabrics/structures to lithology, provide a contrast to the products developed along discontinuity surfaces that been interpreted as submarine hardgrounds (cf., Jaanusson 1961; Kennedy and Garrison 1975; Furisch 1979; Brett and Brookfield 1984) and serve as a set of criteria to distinguish between the two types of stratigraphic discontinuities.

The features of microkarst, i.e., the fossil molds, sparry-calcite-filled casts, and sparry calcite and/or diagenetic sediment filled enlarged solution cavities, indicate that the carbonate sediments during subaerial exposure were indurated, and perhaps were even brittle. Their induration is an important factor because, from the range of products developed during subaerial diagenesis, it is vugular indurated limestone that would stand the most chance of preservation following any erosion by the next marine transgression. Even if erosionally planed and reduced to rocky shore pavement, it is a rock type that will remain in situ. And if the subaerial diagenesis and microkarst features were developed to some metres in depth below the disconformity surface, then erosion would have to remove substantial thickness of indurated limestone to eliminate all evidence of the subaerial exposure. Thus, microkarst expressed as vugular limestone, with its associated sparry calcite fill, and diagenetic sediment fill, stands as one of the more permanent indicators of subaerial exposure, and is the most important indictor of such exposure in these Ordovician limestones. Calcareous sand, while it readily transforms to a palaeosol and will provide abundant nuclei for development of calcrete-ooids, can be without difficulty transported and remobilised. Thus, while lithoclasts (including lithoclasts of limestone with microkarst features), calcrete-ooids, remanié fossils, and reworked subaerially exposed calcareous sands signal that there has been subaerial exposure and pedogenesis, they may have been transported from the source of their development, leaving the stratigrapher to interpret the underlying stratigraphic contact as a subaerial disconformity. As such, they often are more indirect indicators of subaerial exposure. The occurrence of palaeosols is direct evidence of subaerial exposure and pedogenesis, but the preservation of paleosols relies on little or no reworking of this material during the next marine transgression.

The alteration of limestone, and the depth to which diagenetic sediment and illuviation penetrate the limestone profile provide insight into the depth of the vadose zone during the subaerial exposure of the marine limestones. Figure 13 shows penetration of internal sediment for the disconformities in the Bourimbla Limestone Member to generally vary from 1 m to 3 m to 6 m. This would be the main interval of efficient vadose water penetration. At lower levels in the phreatic zone, groundwater alternatively undersaturated and saturated with carbonate, eventually dissolved the geochemically susceptible fossils to form fossil molds filled with sparry calcite.

For the Glenrae Limestone Member, with its thick development of calcrete in eastern sections, the depth of calcretisation would imply a vadose zone of some 50 m. The western section has a calcrete profile more or less 20 m, suggesting a vadose zone of some 20 m depth. The deep vadose zone for the eastern part of the Glenrae Limestone Member is not surprising, as this part of the limestone adjoins the axis of the Molong Volcanic Belt, a positive area to the east that was the determinant of subaerial exposure during deposition of the Daylesford Limestone. A relative higher topographic relief during periods of subaerial exposure, progressively higher to the east towards the axis of the Molong Volcanic Belt, would produce a deep vadose zone in eastern sections of the Daylesford Limestone which would be altered if the parent sediments were porous grainstones. Upper parts of the weathering profile of the eastern sections thus would be continually stripped. Repetitive exposure of limestones along an axis of topographic relief, i.e., along the axis of the Molong Volcanic Belt, would also explain the regressions and the abundance of disconformities throughout the sequence of the Daylesford Limestone, as well as the depth of alteration achieved in some profiles, and the reworking of older limestones as lithoclasts.

Diagenesis and paragenesis of silica in the Daylesford Limestone is a complex issue. Silica is clearly labile in the geological record, and can be dissolved and precipitated depending on the chemistry of pore waters (Walker 1962). Some remobilisation of chalcedonic silica is interpreted to be related to weathering during the Ordovician, as distinct bands of silicification occur beneath some disconformities, as noted earlier. This is not unusual, as silica has been noted in weathering profiles and calcrete profiles by Watts (1980) and Hay and Wiggins (1980), with any available metastable silica dissolved at surface and precipitated at depth. In calcareous soils, silica is re-precipitated at the base of the calcrete profile (Reeves 1970). Clifford (2008), for example, describes the microscale solution and reprecipitation of silica as a laminated patina in a very modern carbonate soil environment where the metastable silica is anthropogenic glass < 100 years old (and geochemically equivalent to metastable biogenic silica), and texturally shows the rapid and labile nature of the silica-and-carbonate interactions. The geochemistry of the solution of silica and its precipitation may be related to the alternation of groundwater pH at the pellicular water microscale from alkaline (and silica dissolving and carbonate precipitating) to acid (and silica precipitating and carbonate dissolving) as discussed by Walker (1962). In the Daylesford Limestone, silicification of limestones is most prevalent in muddy rocks with abundant calcitised triaxon sponge spicules, thus signalling a local source of silica (i.e., metastable opaline silica of sponge spicules) in the soil profile (cf. Watts 1980, and Hay and Wiggins 1980). In the Daylesford Limestone, silicified fossils occur as (rotated) clasts in lithoclast grainstones overlying some disconformities further indicating that silicification was an early diagenetic event associated with pedogenetic processes.

However, being labile, not all silica precipitation is related to disconformities. Elsewhere in the Daylesford Limestone, silica occurs as dark chert nodules (replacement of dark grey, muddy limestone), chalcedonic and quartzose fossil replacements in horizons not associated with disconformities, minor veins and minor euhedra (concentrated in stylolites). These occurrences are silica remobilised during late diagenesis or low-temperature metamorphism.

Dissolution of limestone in the vadose and phreatic zone suggests that the Ordovician environment had moderate rainfall, i.e., it was not arid, wherein the evaporation would have markedly exceeded precipitation. Carbonate sediments and rocks exposed subaerially in arid regions tend to develop specific types of calcrete (pisolites, laminar calcrete), red soils, and lesser leaching because of the deficit of freshwater. These features are absent from the rocks of the Daylesford Limestone.

There has been discussion in the literature that, with atmospheric carbon estimated to have been ~500 times more abundant in Hadean time than at present, and its concentration gradually decreasing since then due to storage in sedimentary rocks, rain pH has been gradually increasing through geologic time, such that groundwaters are less acidic today than they were in the distant past (Jutras et al. 2009). Based on studies of pre-Silurian palaeosols developed on primary rocks, however, Jutras et al. (2009) suggest that groundwater pH was, on average, highest shortly before the Late Ordovician to Silurian proliferation of root-forming land plants, i.e., there was a greater tendency for alkalinity during this time period than during previous and subsequent geologic periods. The results from the Daylesford Limestone provide some insight into this argument: the solution of limestones in subaerial environments during the Ordovician suggests that both rainwater and percolating groundwater (as vadose water and phreatic water) were sufficiently acidic to drive dissolution of limestone as a major and prominent process in the surface and near-surface environments. While vadose processes may involve alternating alkalinity and acidity at pellicular water scale, alkaline rainwater and groundwater would not drive such marked dissolution. Weathering of primary rocks to form palaeosols in the Middle Ordovician, based on mineral transformations as described by Jutras et al. (2009), may have been in an alkaline groundwater environment, but this should not be taken to imply that globally groundwater also was alkaline.

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